HV-MAPS for the Mu3e Experiment

2nd ATLAS HV-MAPS Workshop

Geneva, July 2, 2015

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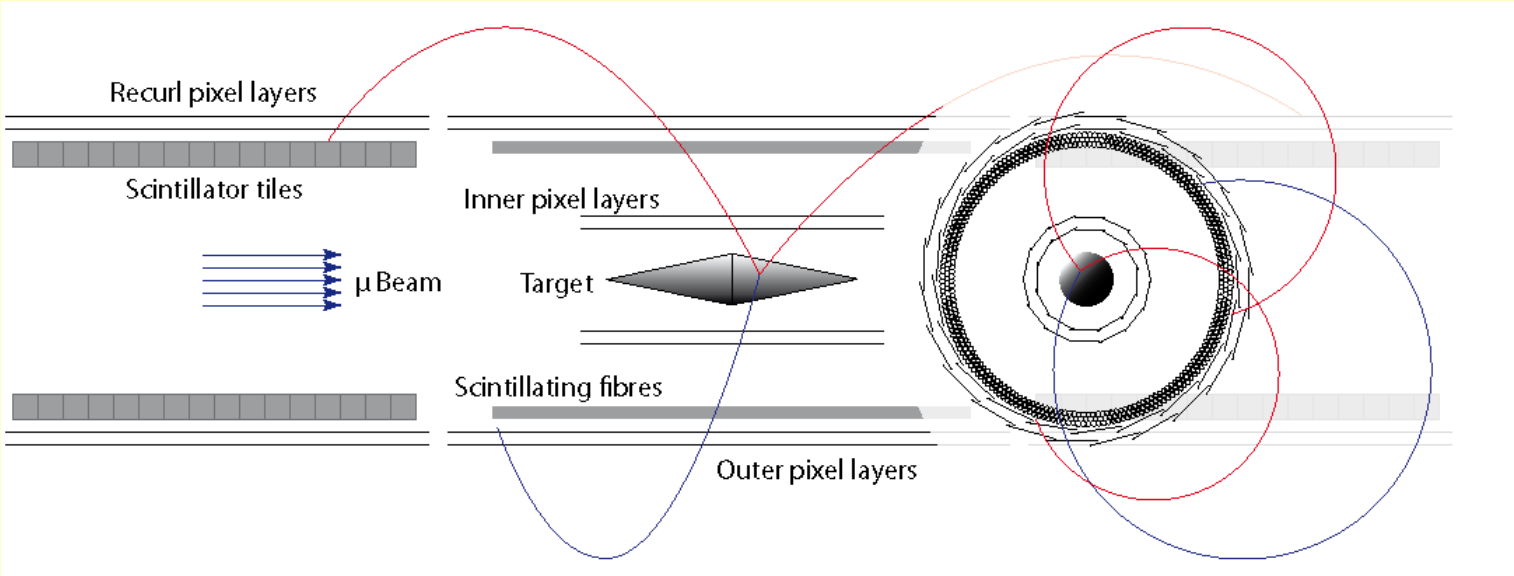
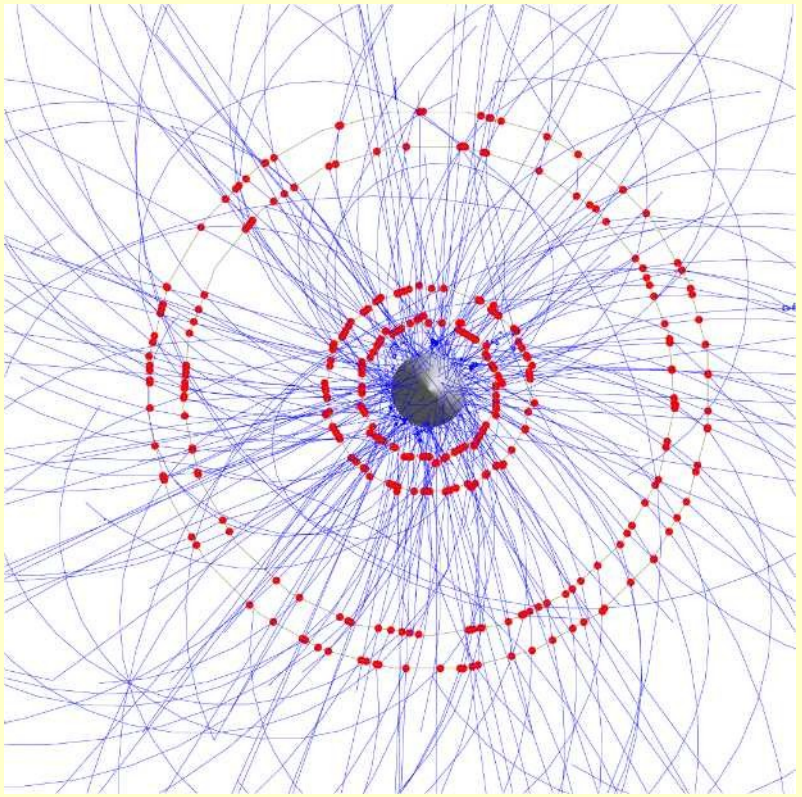
for the Mu3e Pixel Group



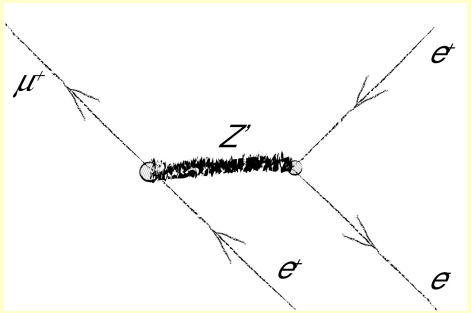
The Mu3e Experiment

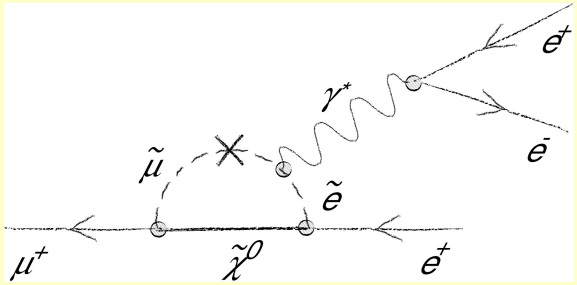
- Search for LFV decay: **μ → eee**
- Single event sensitivity of
  - **~10^{-15}** Phase I
  - **<10^{-16}** Phase II
- Stopped muon rate **10^8/s (>10^9/s)**
- 10 (>100) tracks within 50ns



All silicon tracker

- Sensitive to New Physics:

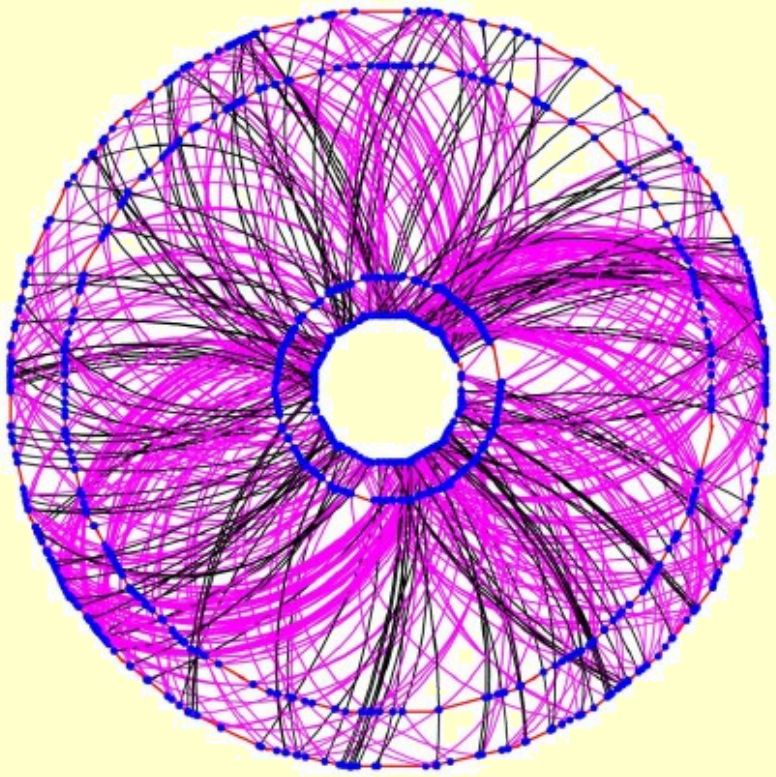




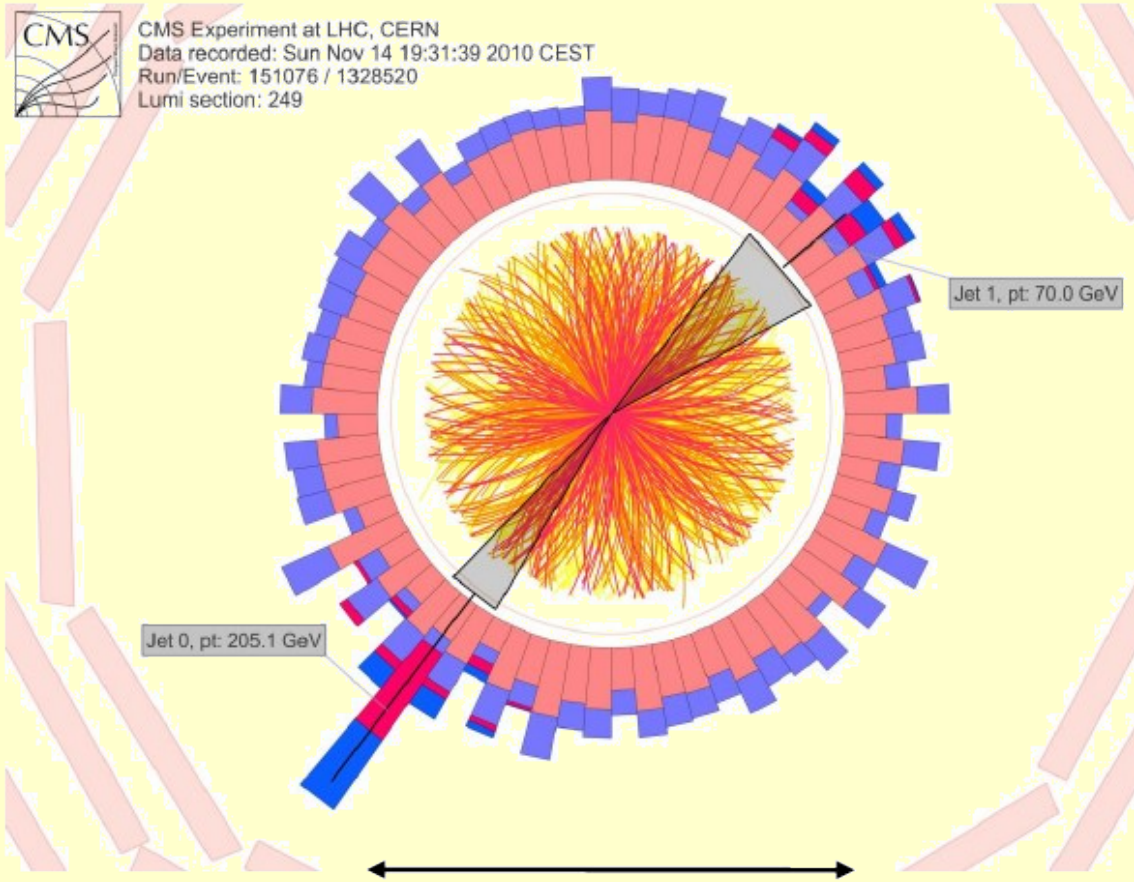
Discussed in Research Proposal:
→ arXiv:1301.6113

Pileup

Mu3e: reconstructed 4-hit tracks

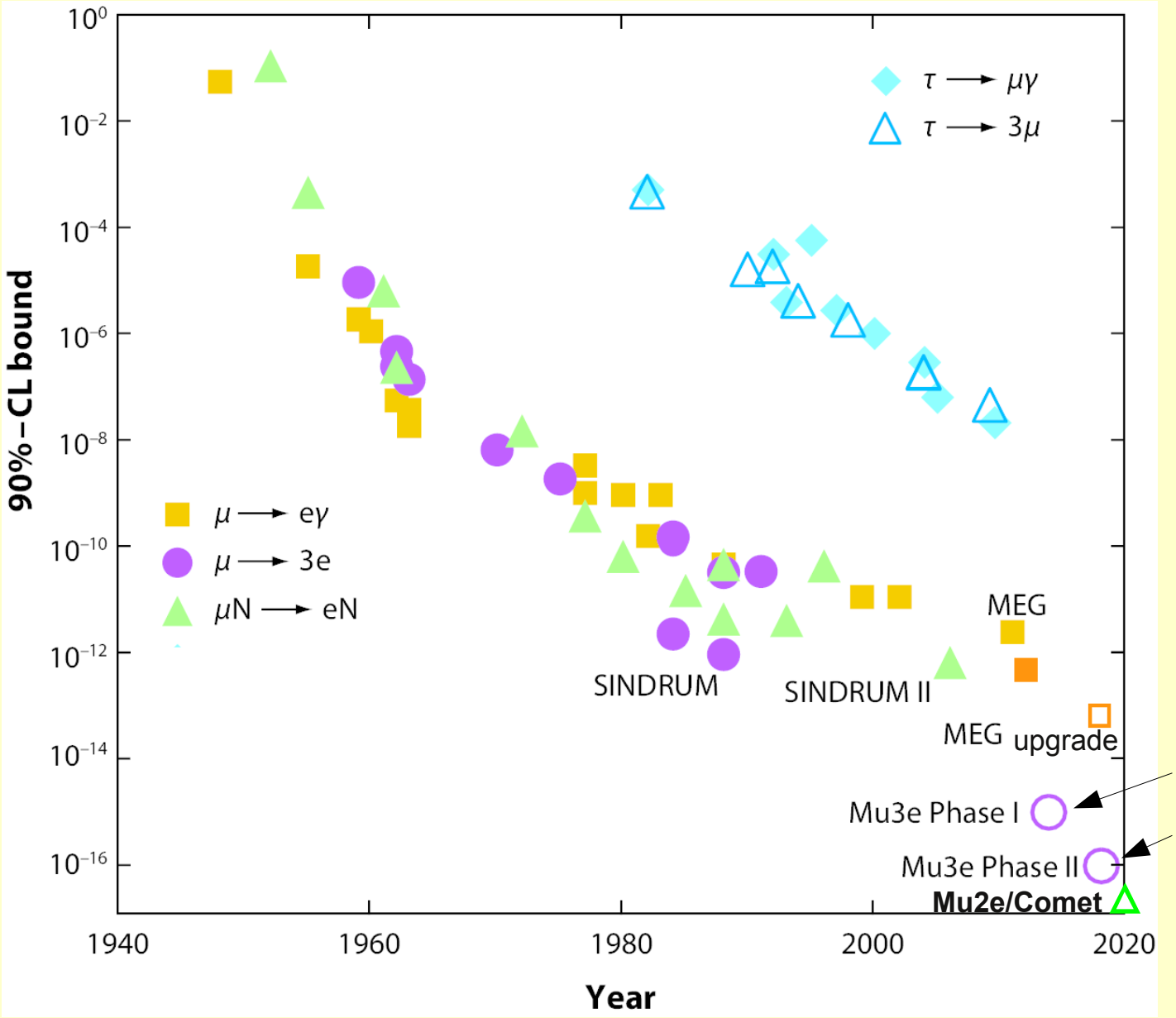


≈16 cm
Readout in frames of 50 ns
E ~ 10-50 MeV



≈2.5 m
Collision every 25 ns
E ~ 200 GeV

History of LFV Decay experiments

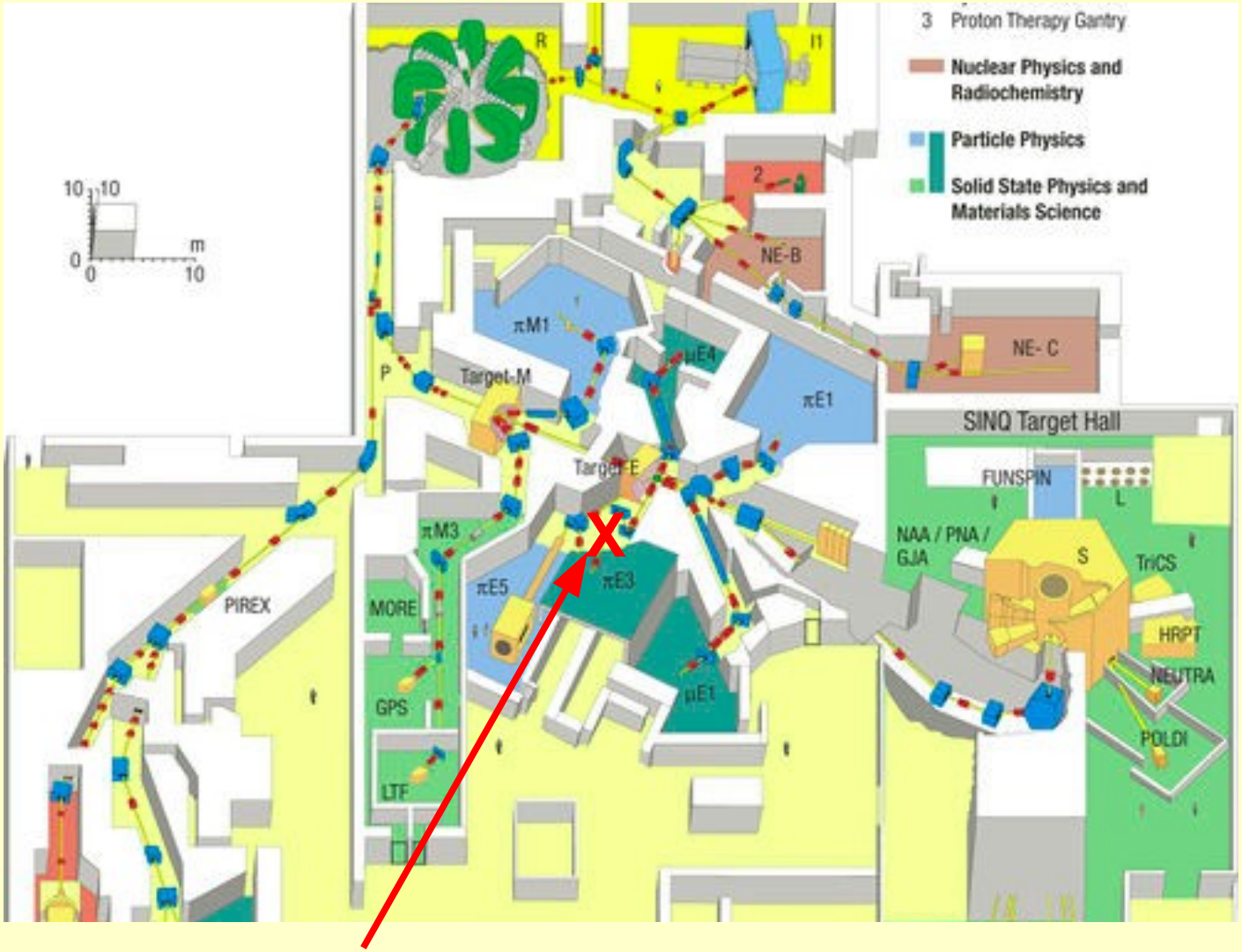


$B(\mu^+ \rightarrow e^+e^+e^-)$

Phase I: 10^{-15}

Phase II: 10^{-16}

PSI Beam Facilities for Mu3e



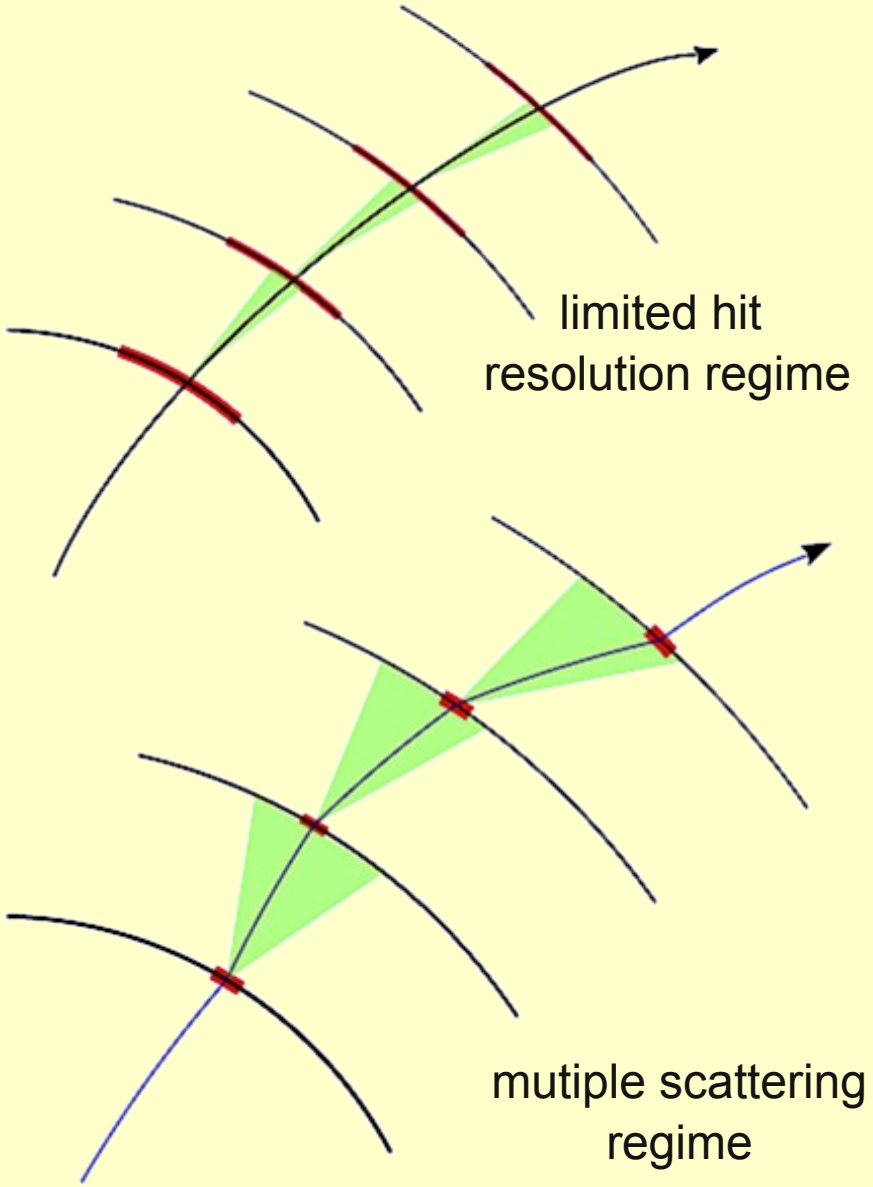
Phase I: ~10^8 muons/s

PiE5: New Compact Muon Beam Line

Phase II: >10^9 muons/s

HiMB: High Intensity Muon Beam Line

Kinematic Resolution + Multiple Scattering



- Muon decay:

  → electrons in low momentum range

  p < 53 MeV/c

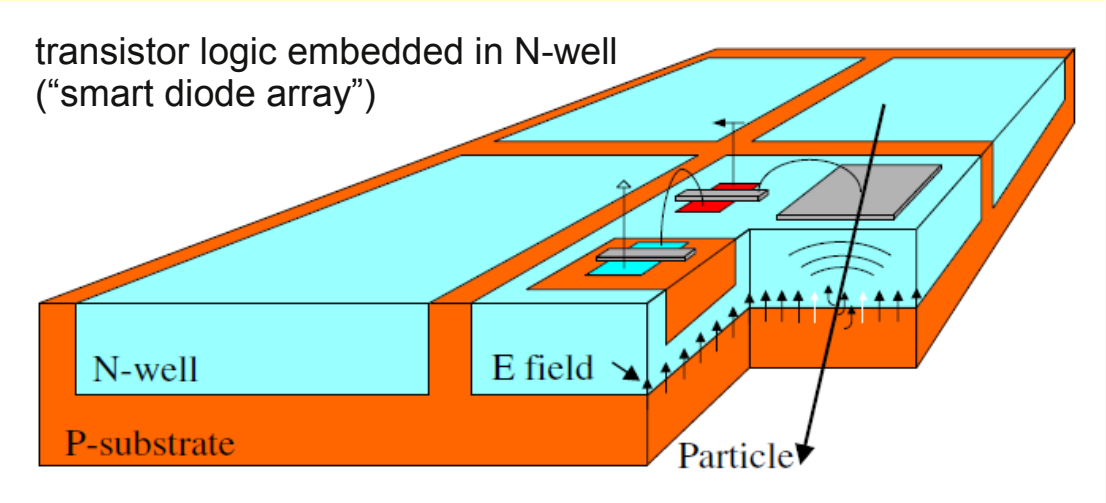
- Multiple scattering is dominant!

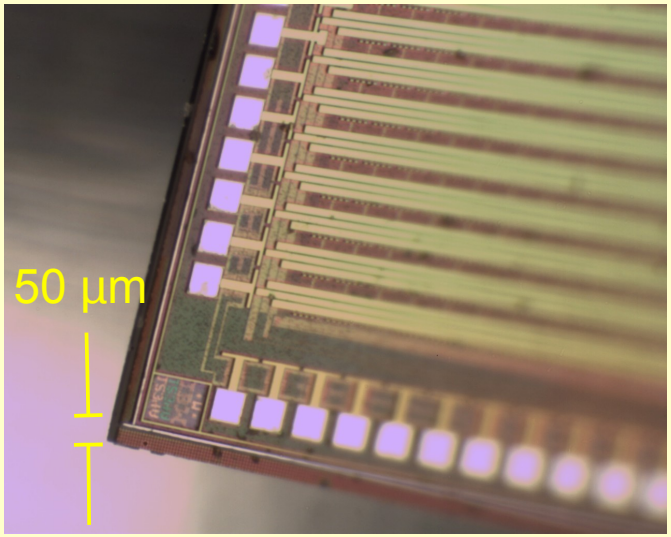
→ **Need thin, fast and high resolution tracking detectors operated at high rate of ~ 10^9 particles/s**

$$\Theta_{MS} \sim \frac{1}{P}\sqrt{X/X_0}$$

Silicon Pixel Detector

I.Peric, P. Fischer et al., NIM A 582 (2007) 876 (ZITI Mannheim, Uni Heidelberg)





Technology Choice

High Voltage Monolithic Active Pixel Sensors (HV-MAPS)

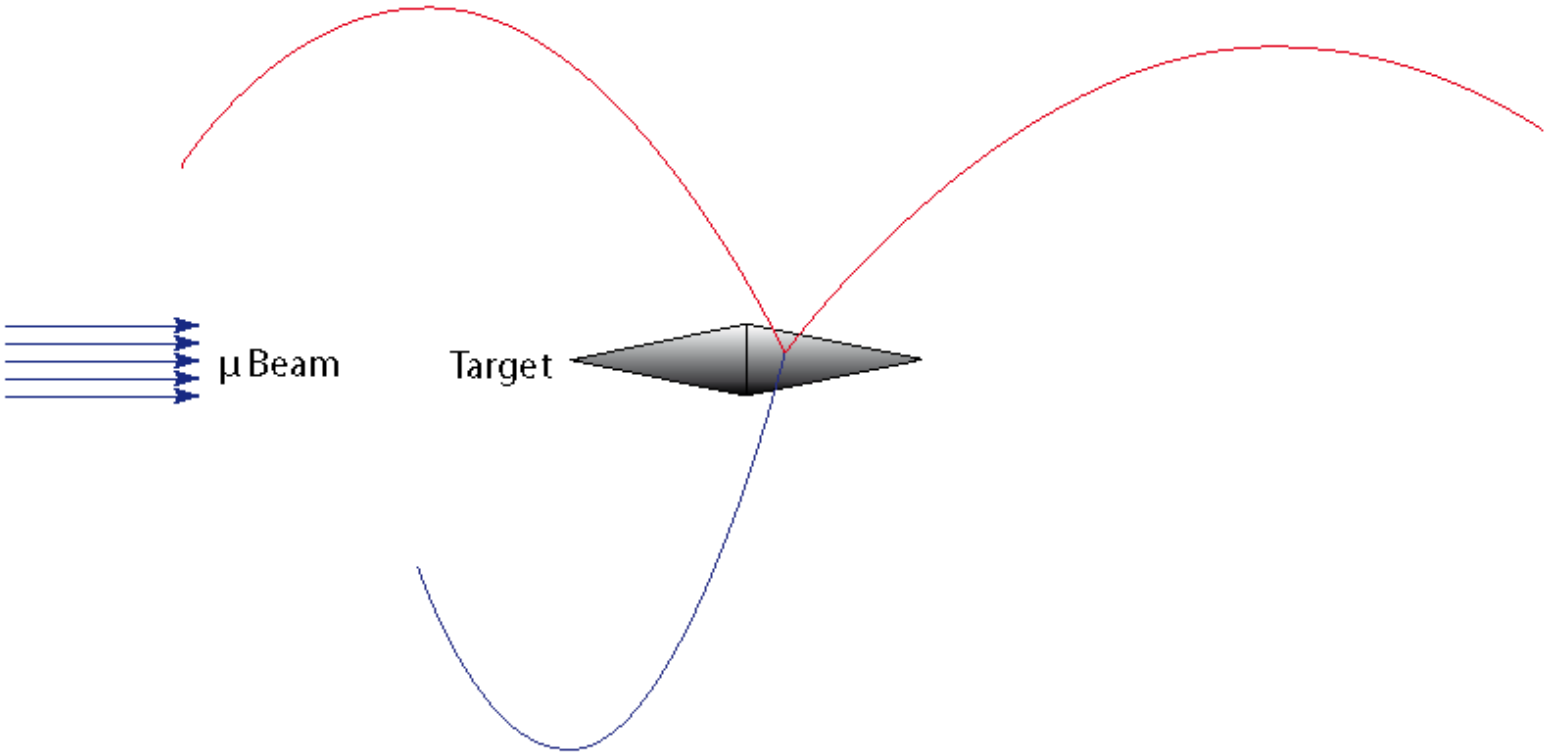
- high precision → pixels **80 x 80 µm²**
- can be "thinned" down to ~**35-50 µm** (~ 0.0005 X_0)
- low production costs (standard HV-CMOS process, 60-80 V)
- **active sensors → hit finding + digitisation + readout**
- triggerless and fast readout (LVDS link integrated)
- low power: → **250** mW/cm²

Mu3e Baseline Design - Phase I

10^8 muons / sec

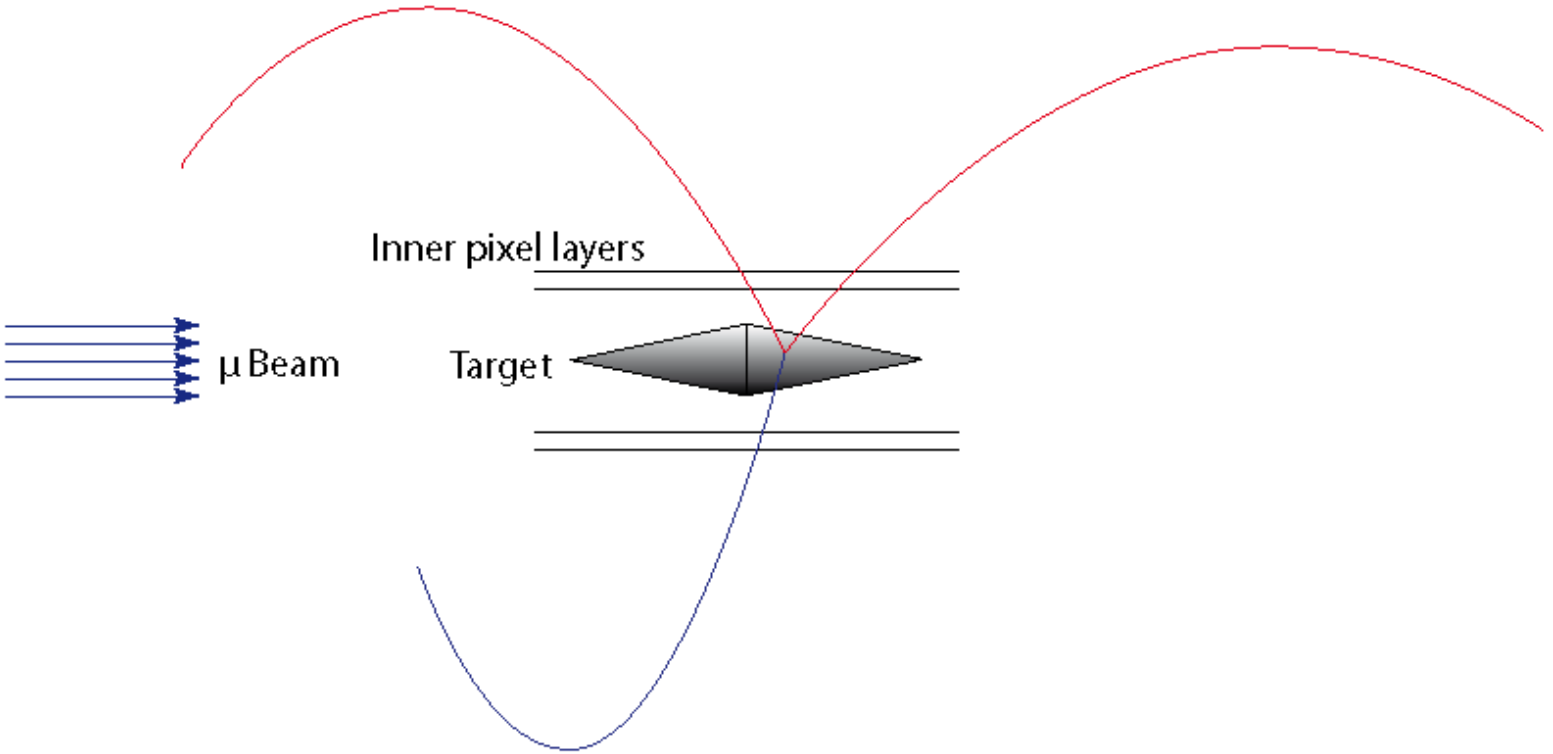
E_{kin} = 28 MeV

Mu3e Baseline Design



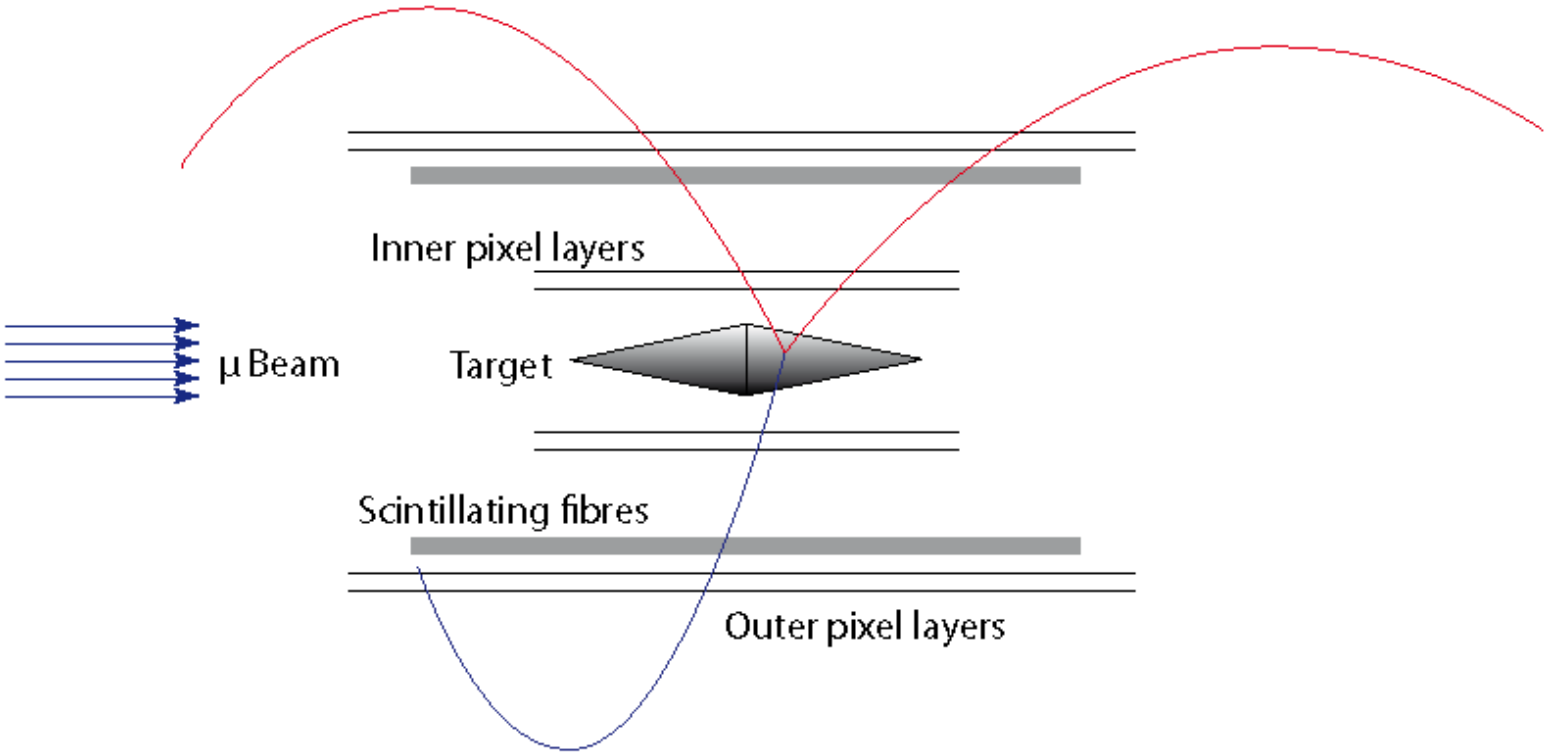
Very thin hollow target → low multiple scattering

Mu3e Baseline Design



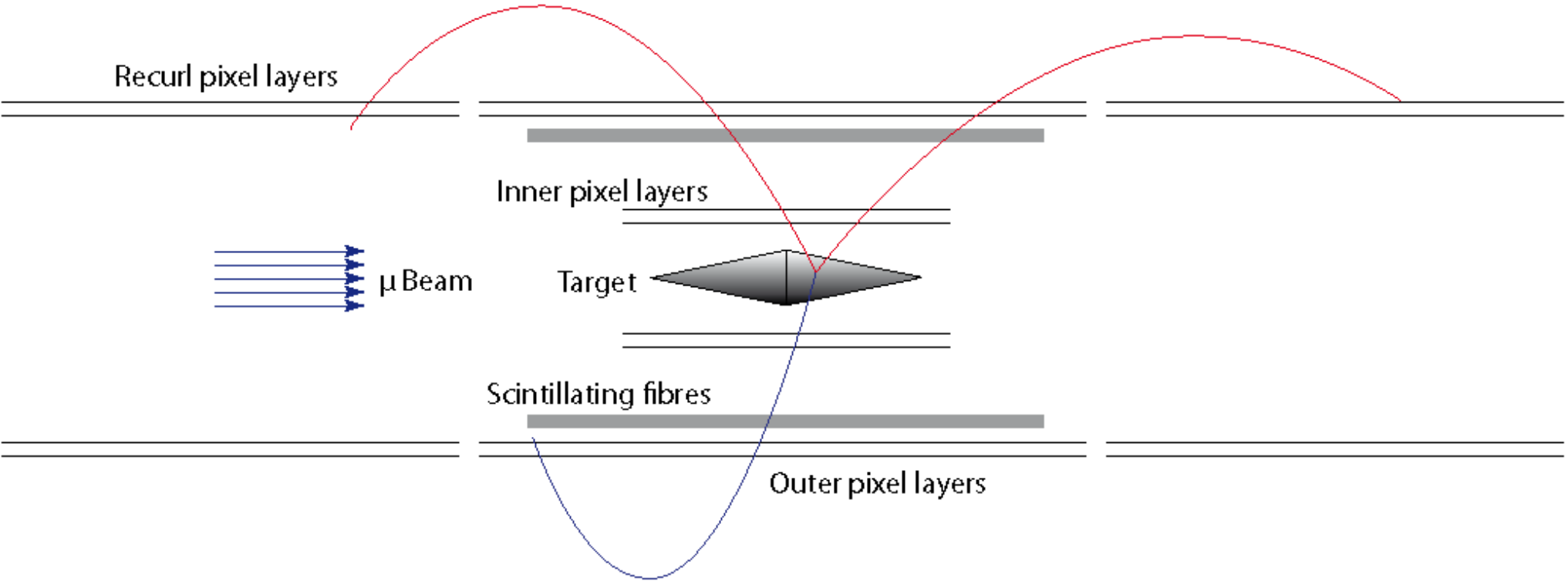
Very thin silicon layers (50 μm) → reduces multiple scattering

Mu3e Baseline Design



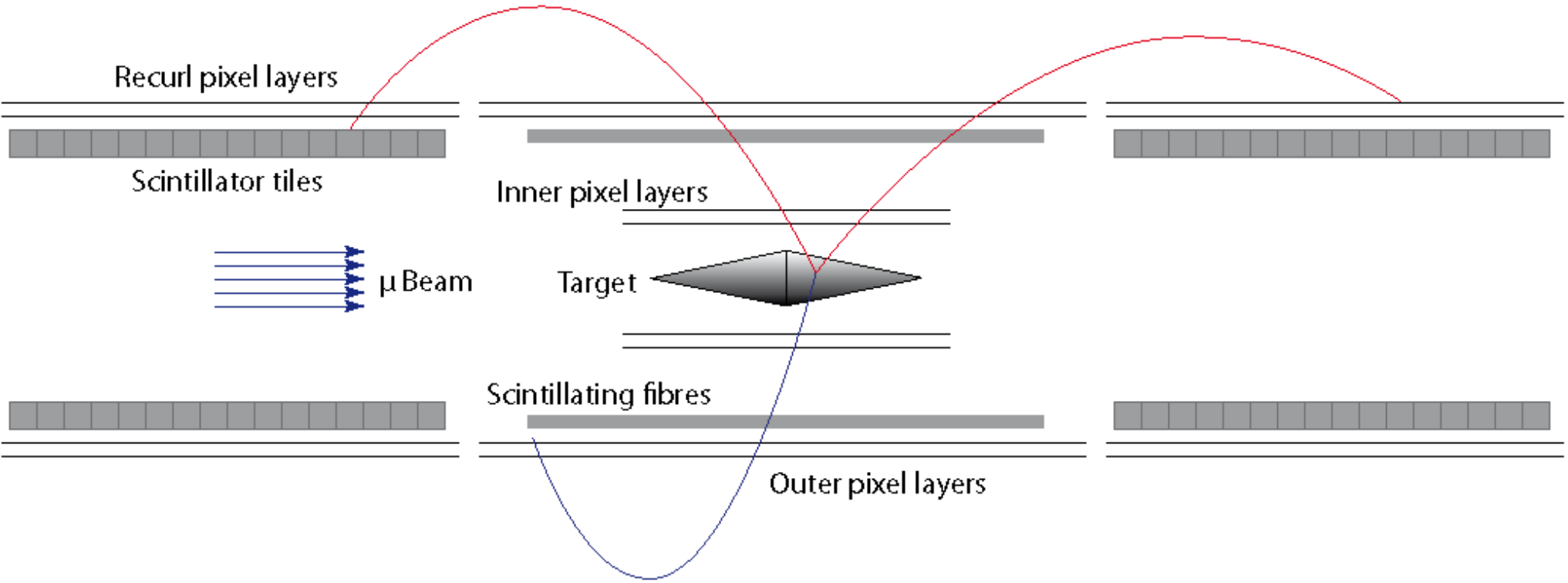
Good time resolution of <1ns → reduces accidentals

Mu3e Baseline Design



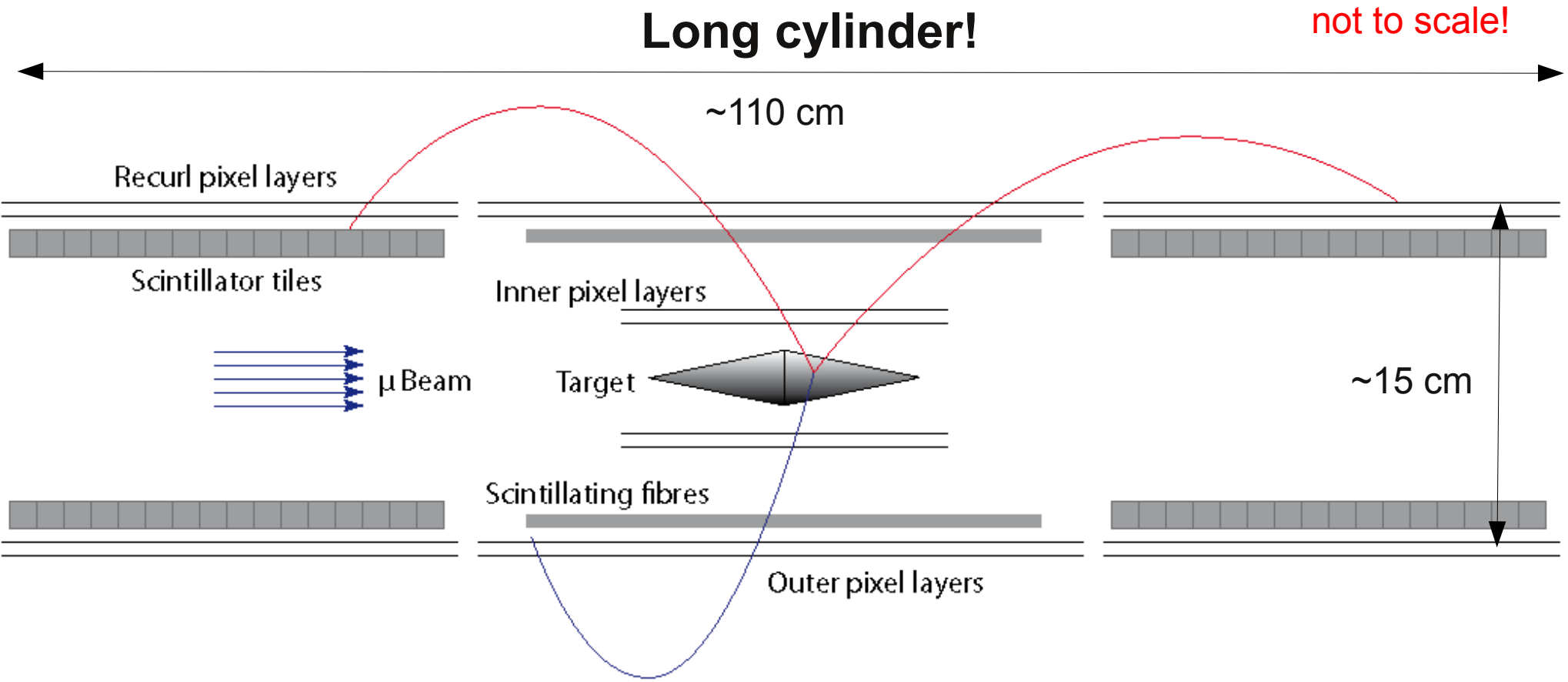
Helium atmosphere → improves momentum resolution of recurling tracks

Mu3e Baseline Design



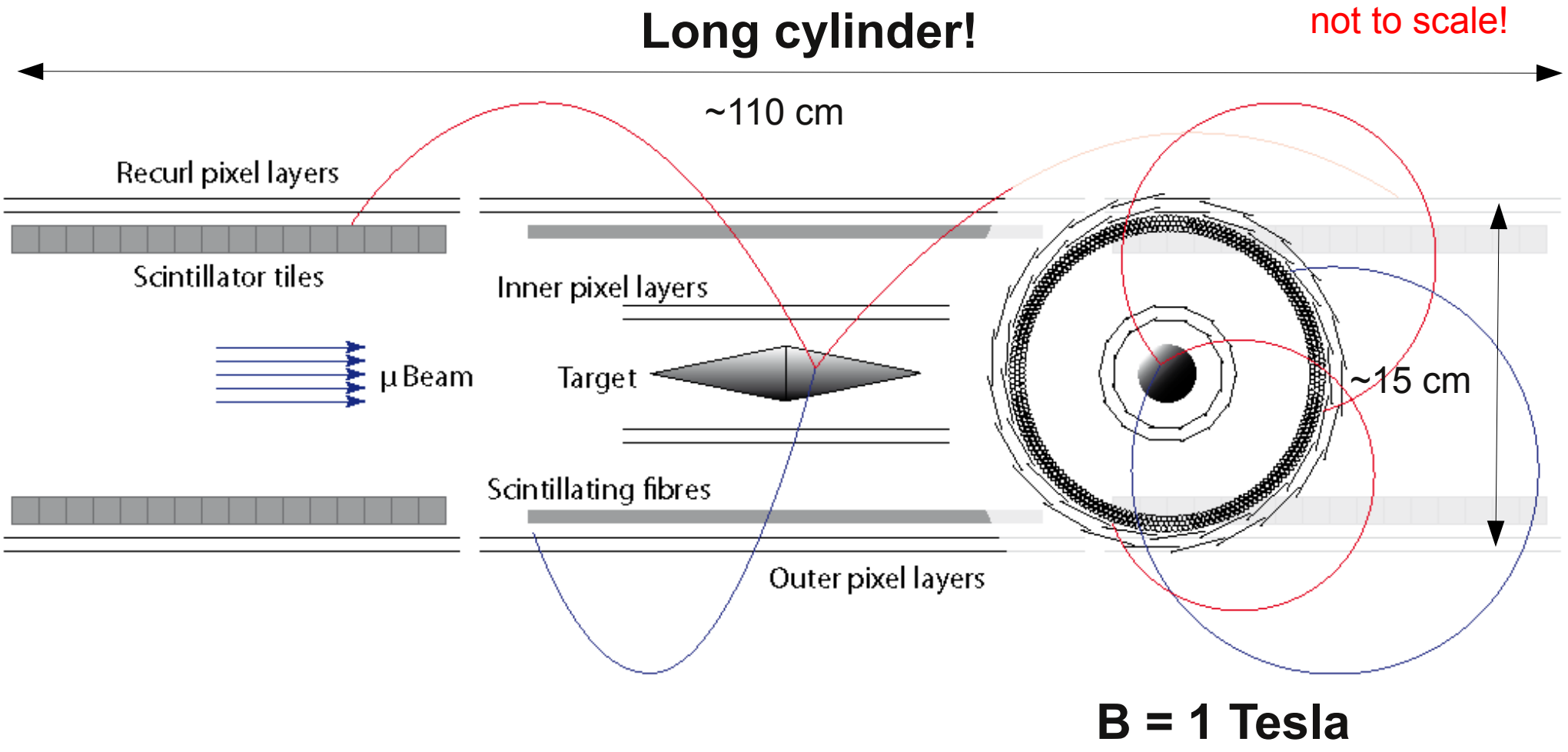
Good time resolution of ~0.1ns → reduces accidentals

Mu3e Baseline Design



Very compact design → not much space for services!

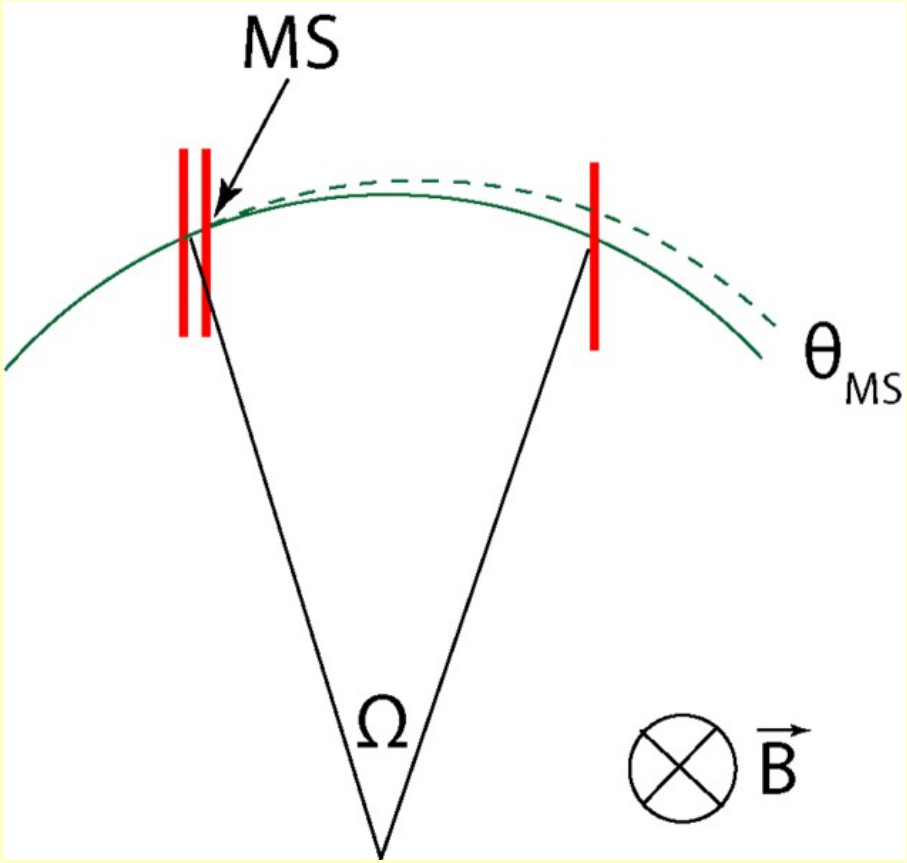
Mu3e Design for Phase I



Homogenous magnetic field → allows fast online reconstruction

Momentum Resolution in MS Regime

- Standard spectrometer:



$$\frac{\sigma_p}{P} \sim \frac{\Theta_{MS}}{\Omega}$$ (linearised)

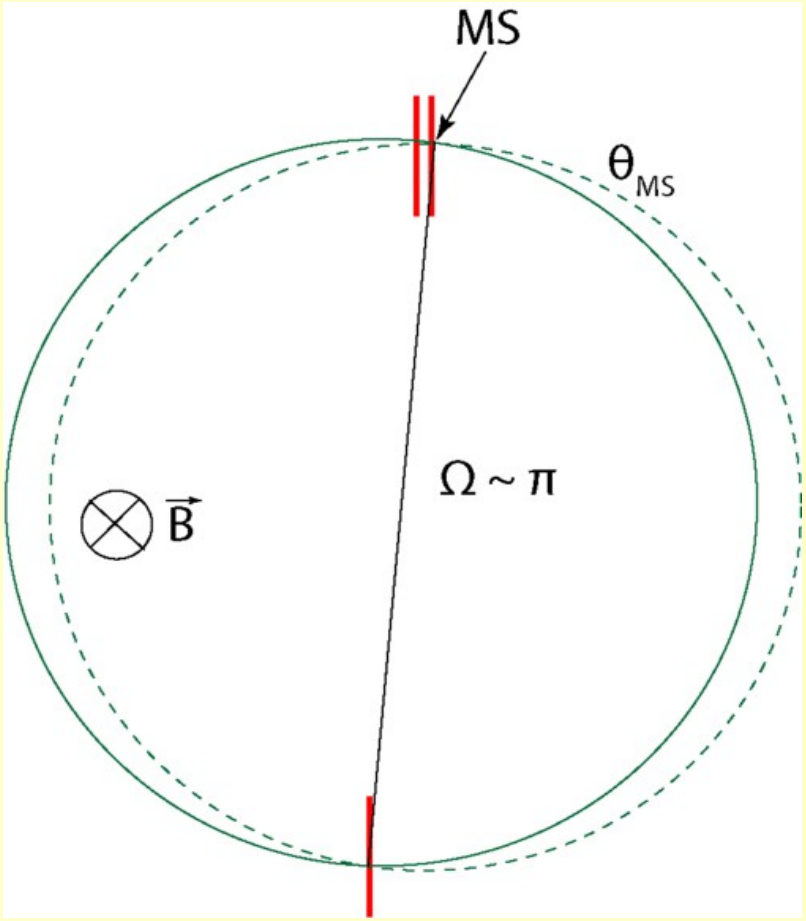
precision requires large lever arm:

→ large bending angle Ω

→ also relevant for LHC

Momentum Resolution in MS Regime

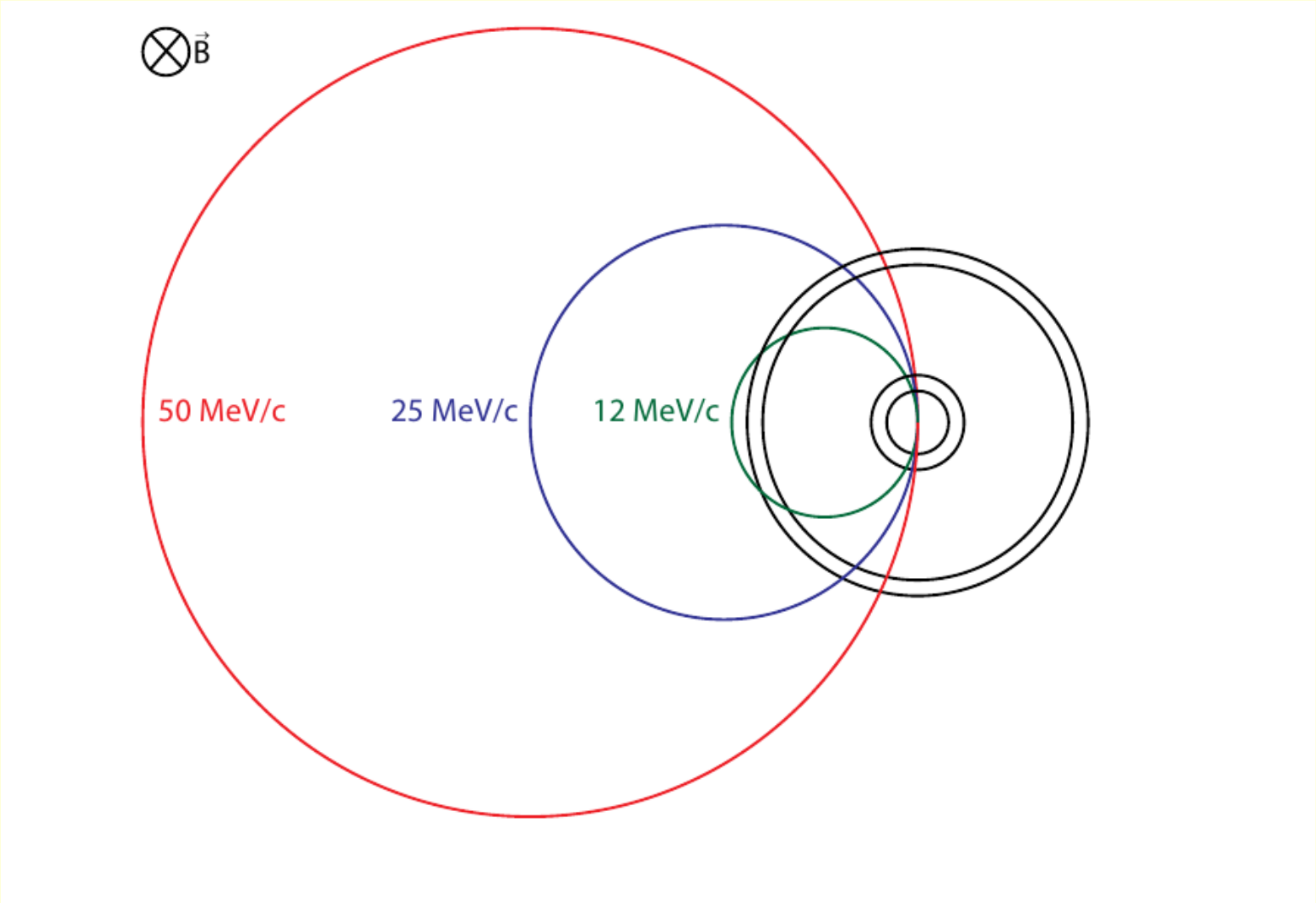
- "Half turn" spectrometer:



$$\frac{\sigma_p}{P} \sim O\left(\Theta^2_{MS}\right)$$

- **best precision for half turn tracks**
- **measure recurlers !**

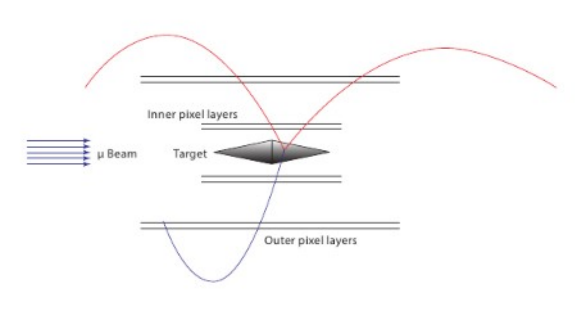
Tracking Design Considerations



→ compromise between precision and acceptance

Staged Approach

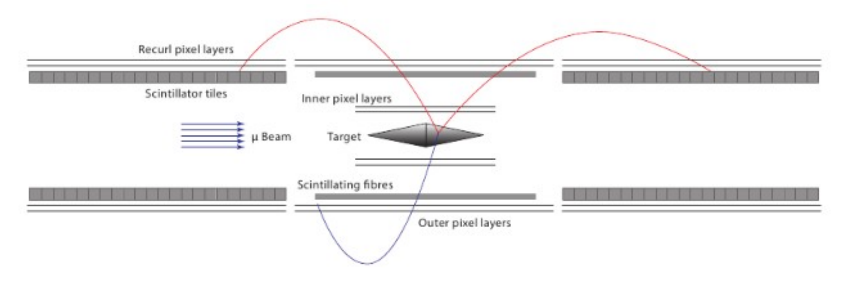
Phase IA:
rate ≤ 10^7 muons/s



only central Pixel

- minimal setup
- add timing detectors if available

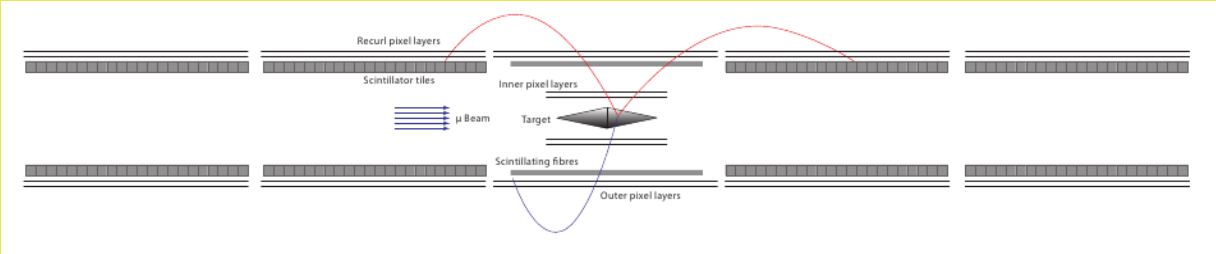
Phase IB:
rate ~ 10^8 muons/s



+ inner recurl detectors
+ time of flight system

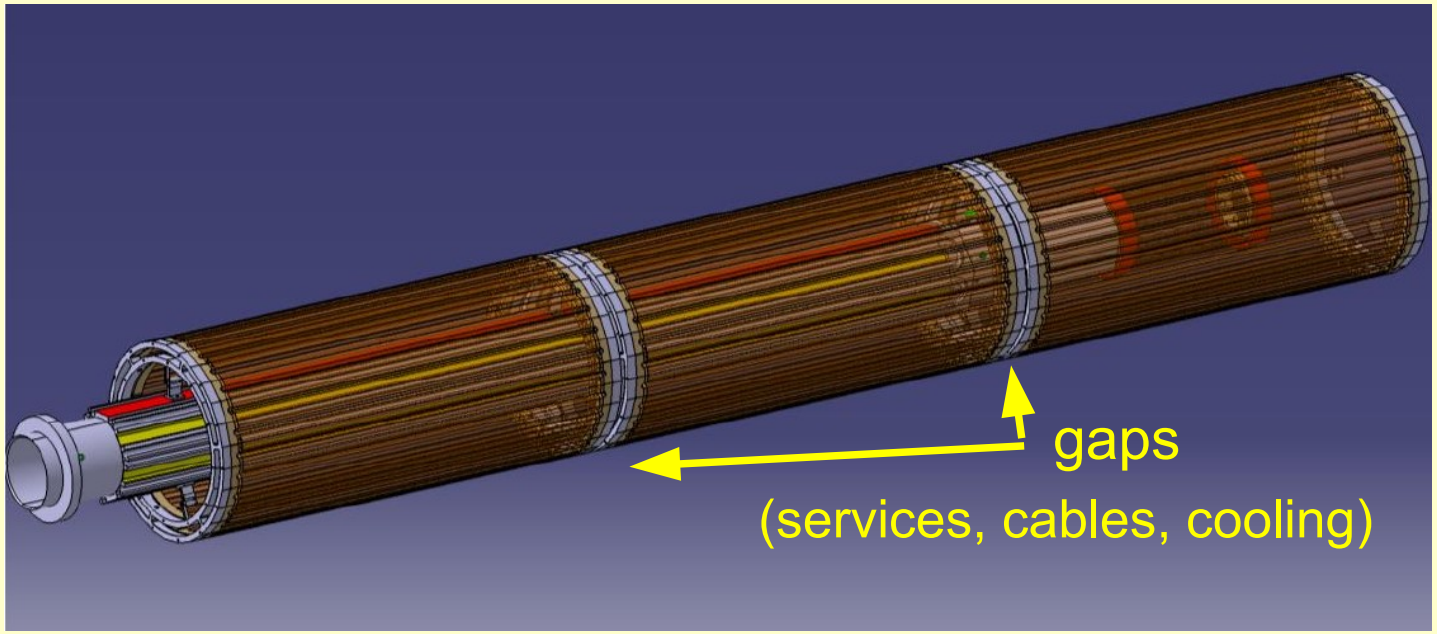
Phase II:
rate ~ 10^9 muons/s

(later upgrade)

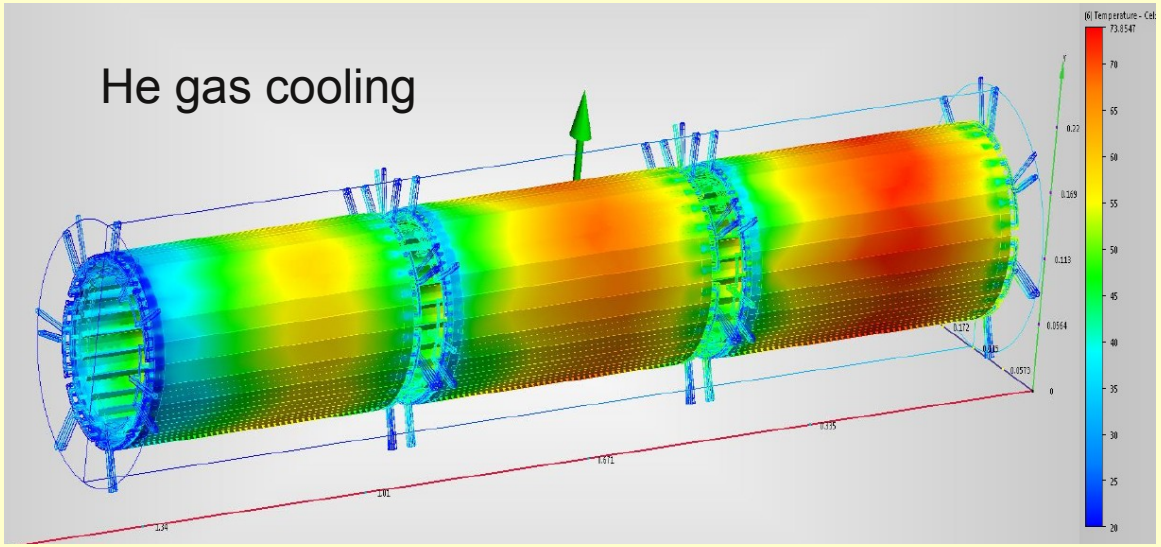


+ outer recurl detectors
+ outer tiles

Realistic Pixel Detector Design



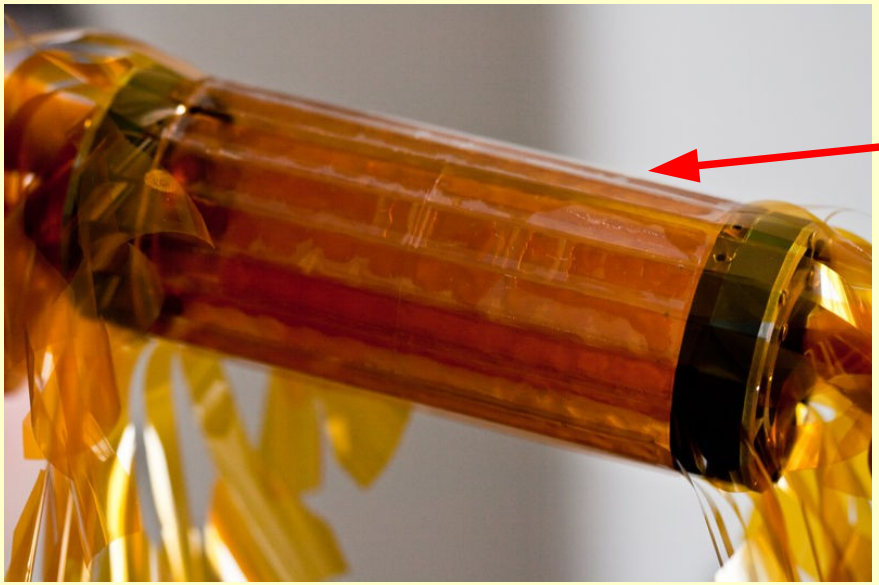
detailed cooling simulations
and tests in lab



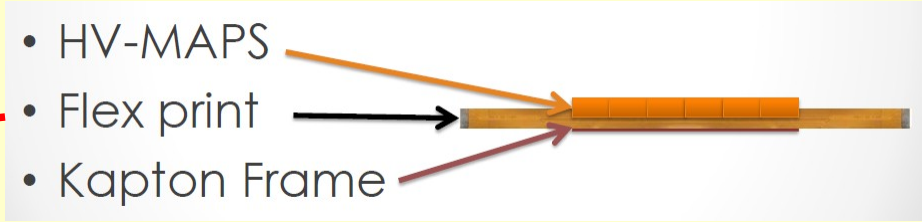
Mu3e-Tracker Construction

Ultra-thin detector mock-up:

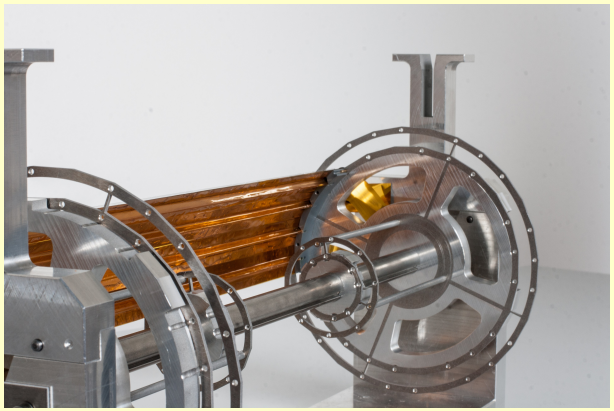
- sandwich of 25 µm Kapton®
- 50 µm glass (instead of Si)



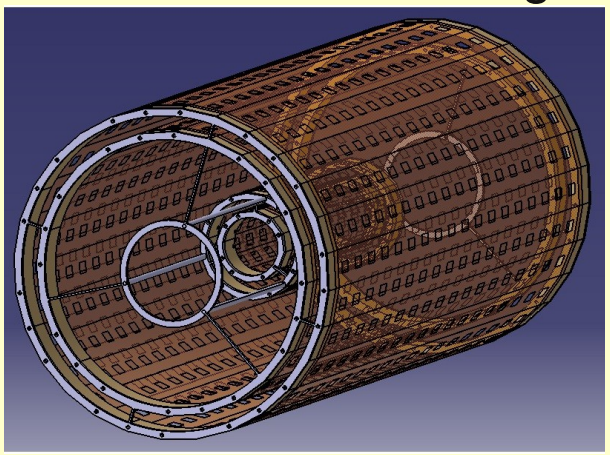
Sandwich design:



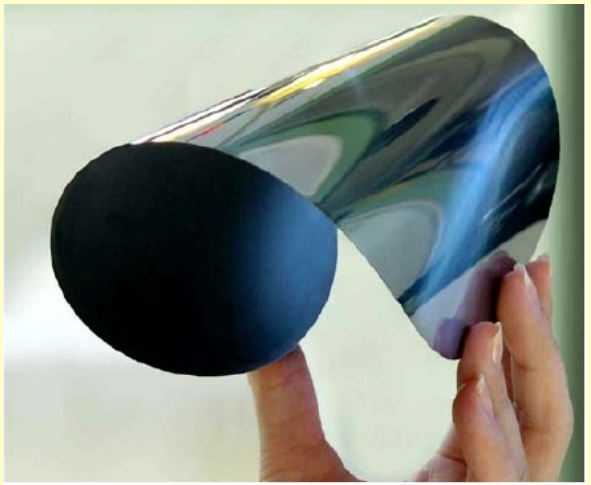
→ **X/X_0 ~ 0.1% per layer**



CAD drawing



50 µm silicon wafer

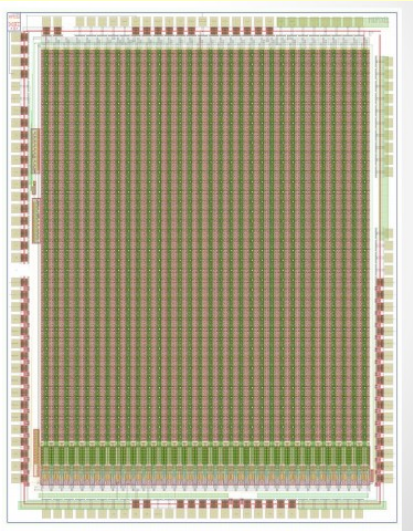


Mupix Generation

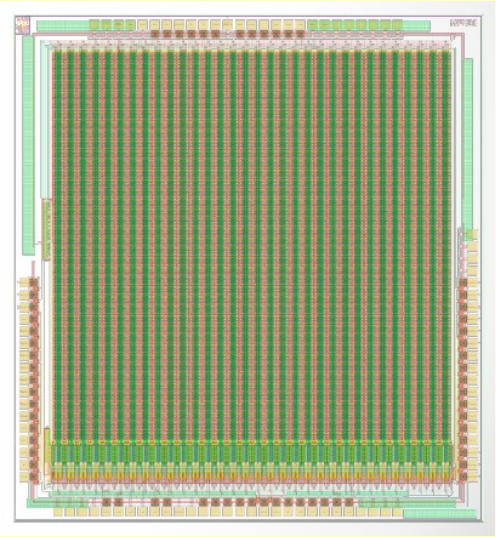
	in-pixel CSA	2nd-stage CSA	pixel size (mu^2)	comparator	serial Gigabit link	internal state machine
Mupix4	**X**		**92 x 80**	**standard**		
Mupix6	**X**	**X**	**103 x 80**	**new**		
Mupix7	**X**	**X**	**103 x 80**	**new**	**X**	**X**

Number of pixels: **40 x 32**

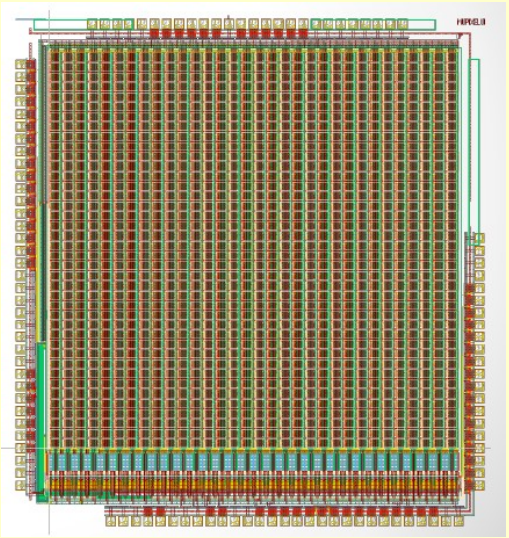
Mupix 5



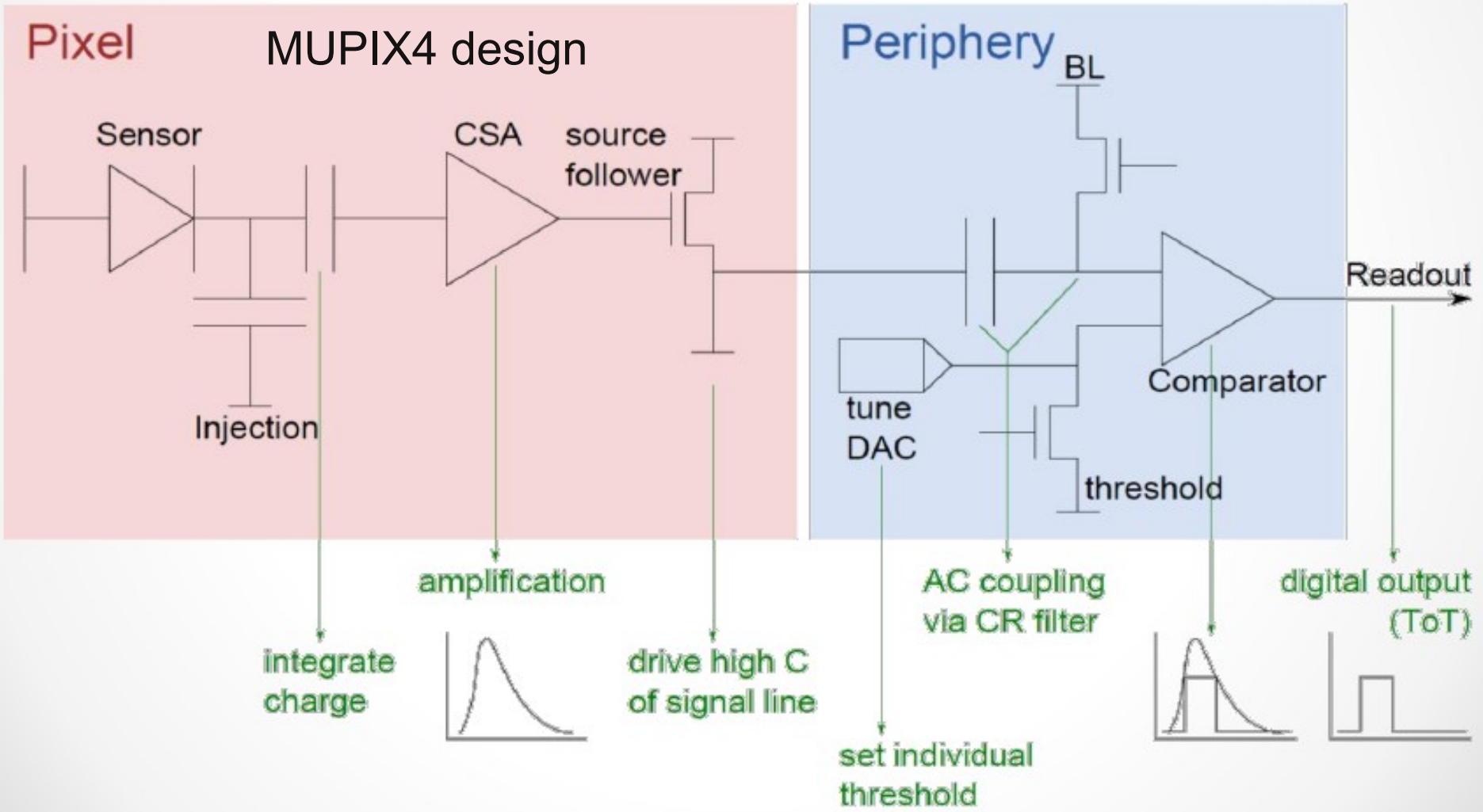
Mupix 6



Mupix 7

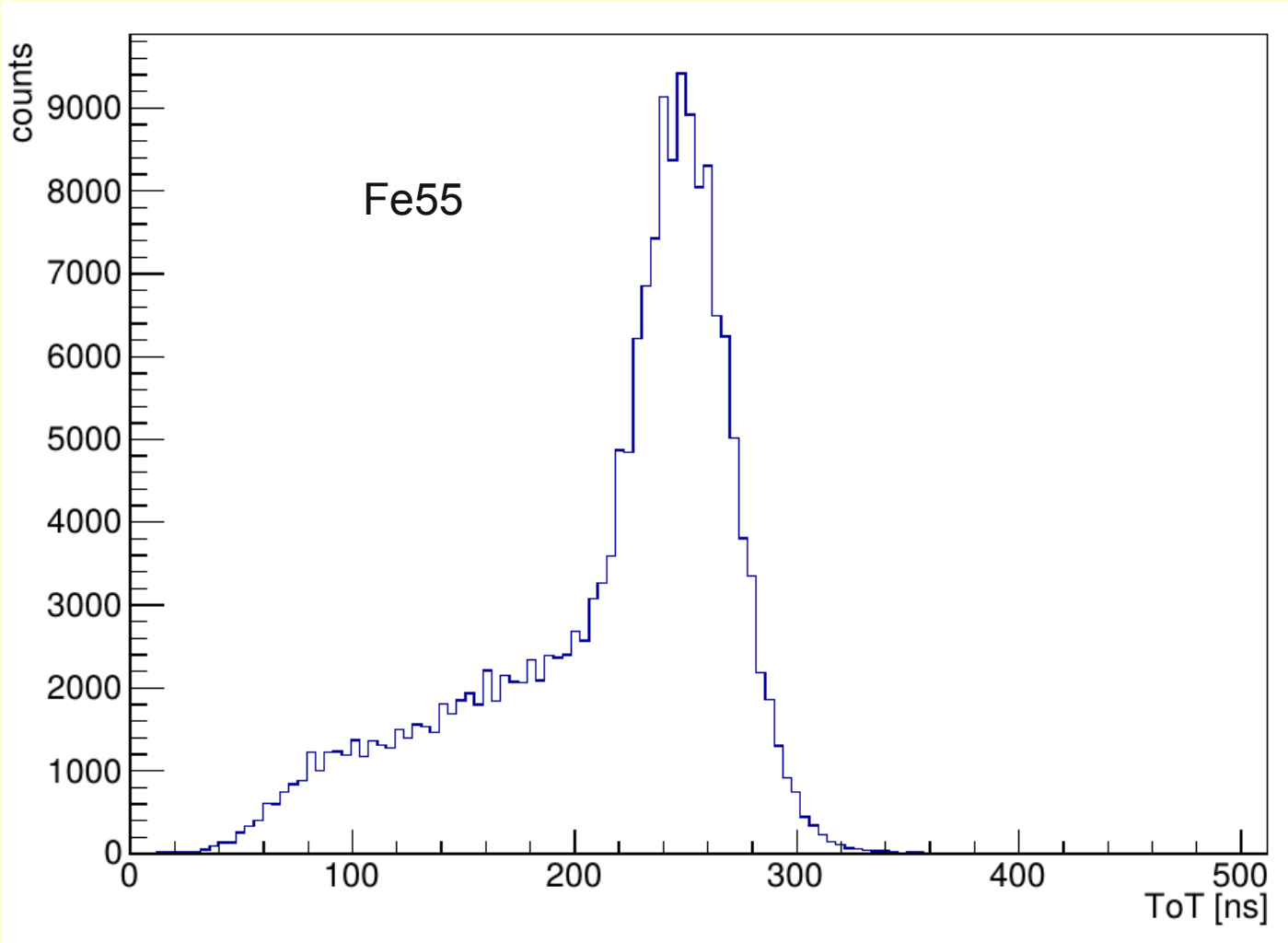


Sensor + Analog + Digital



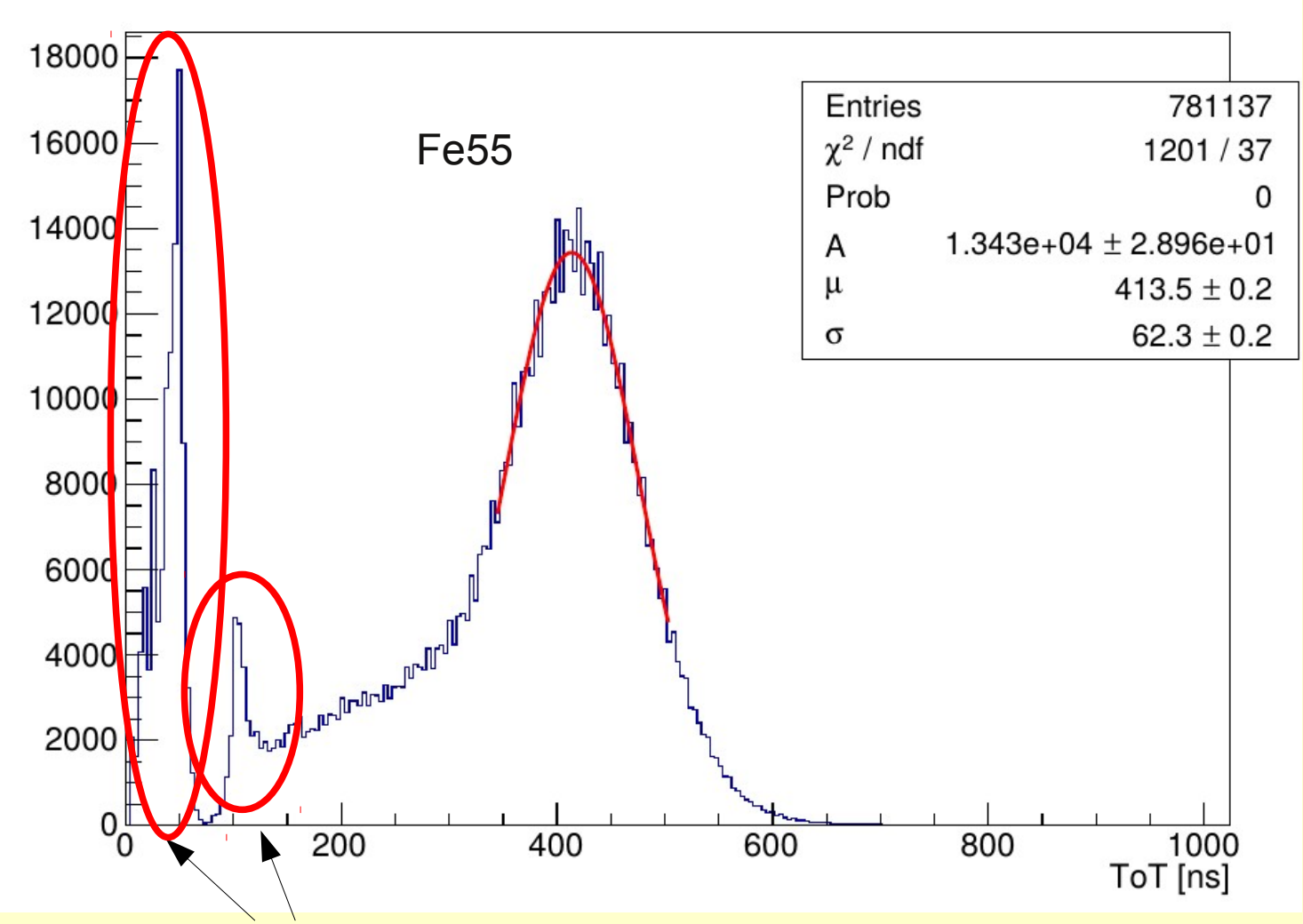
ToT of Fe55 Peak with Mupix4

Single stage amplifyer (in-pixel & periphery)



ToT of Fe55 Peak with Mupix6/7

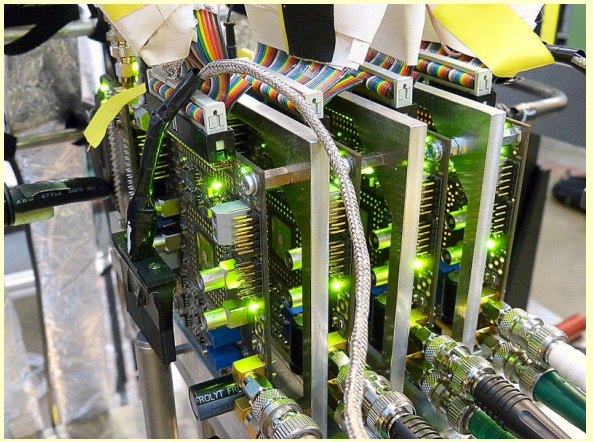
Double stage amplifyer (in-pixel & periphery) + different comparator circuitry



oscillations around threshold

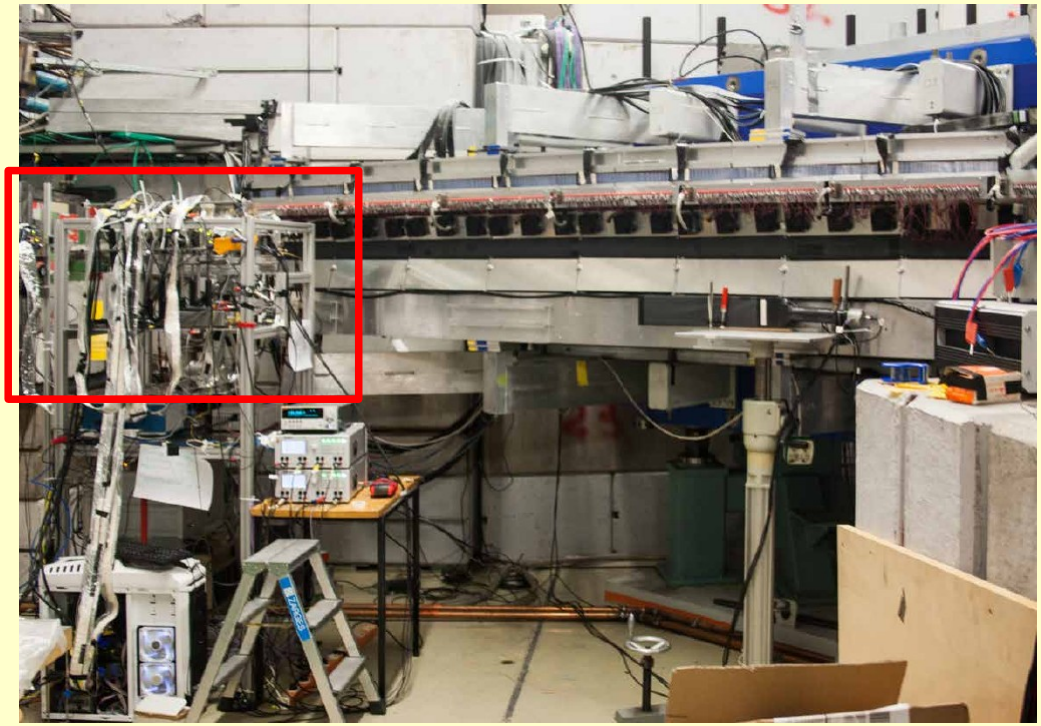
Mupix Beam Telescope

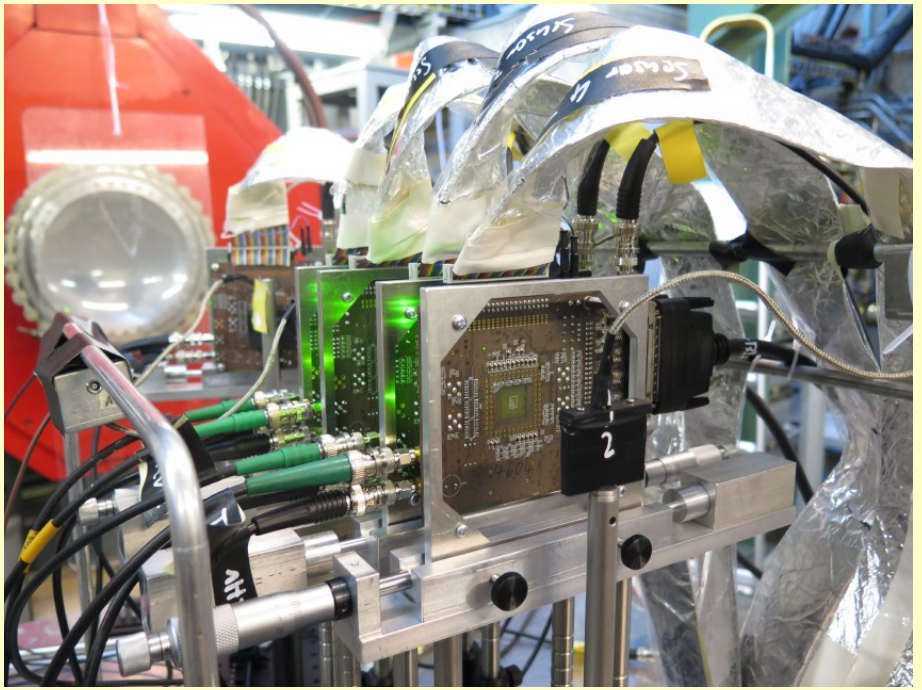
- 4 layers of Mupix prototype chips
- state machine outside MAPS
- synchronous readout at ~1 MHz achieved



Paul Scherrer Institute

MAMI (Mainz)

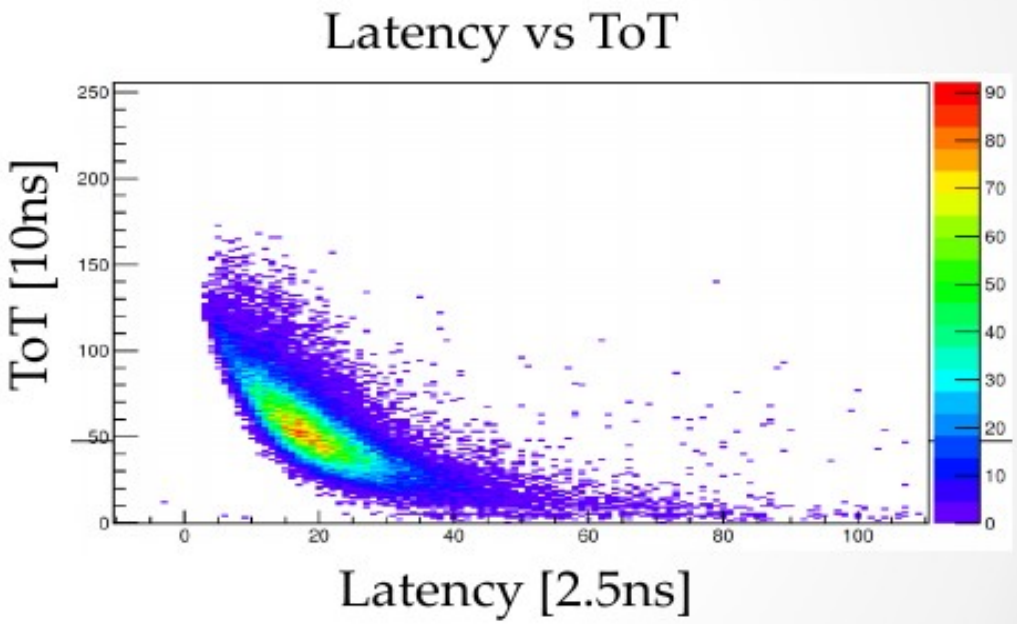




Timewalk

- Latency
  - Difference of rising edge: Tile detector pulse - Time over Threshold
- vs Time over threshold signal

measurement at PSI



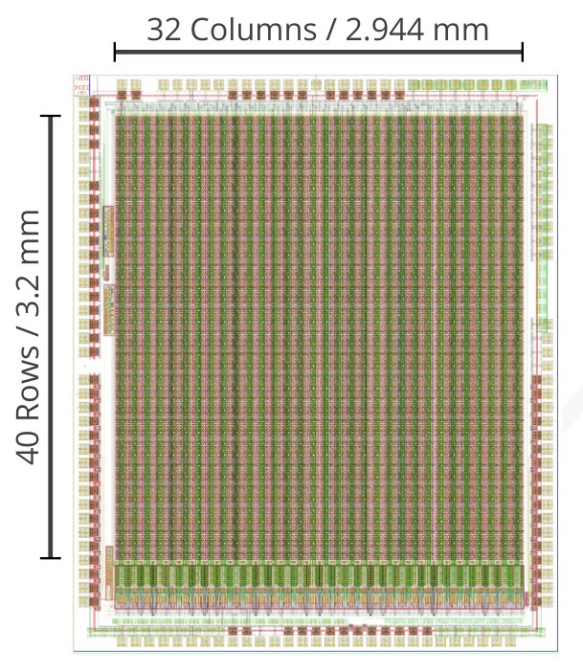
time resolution: **sigma < 10 ns**

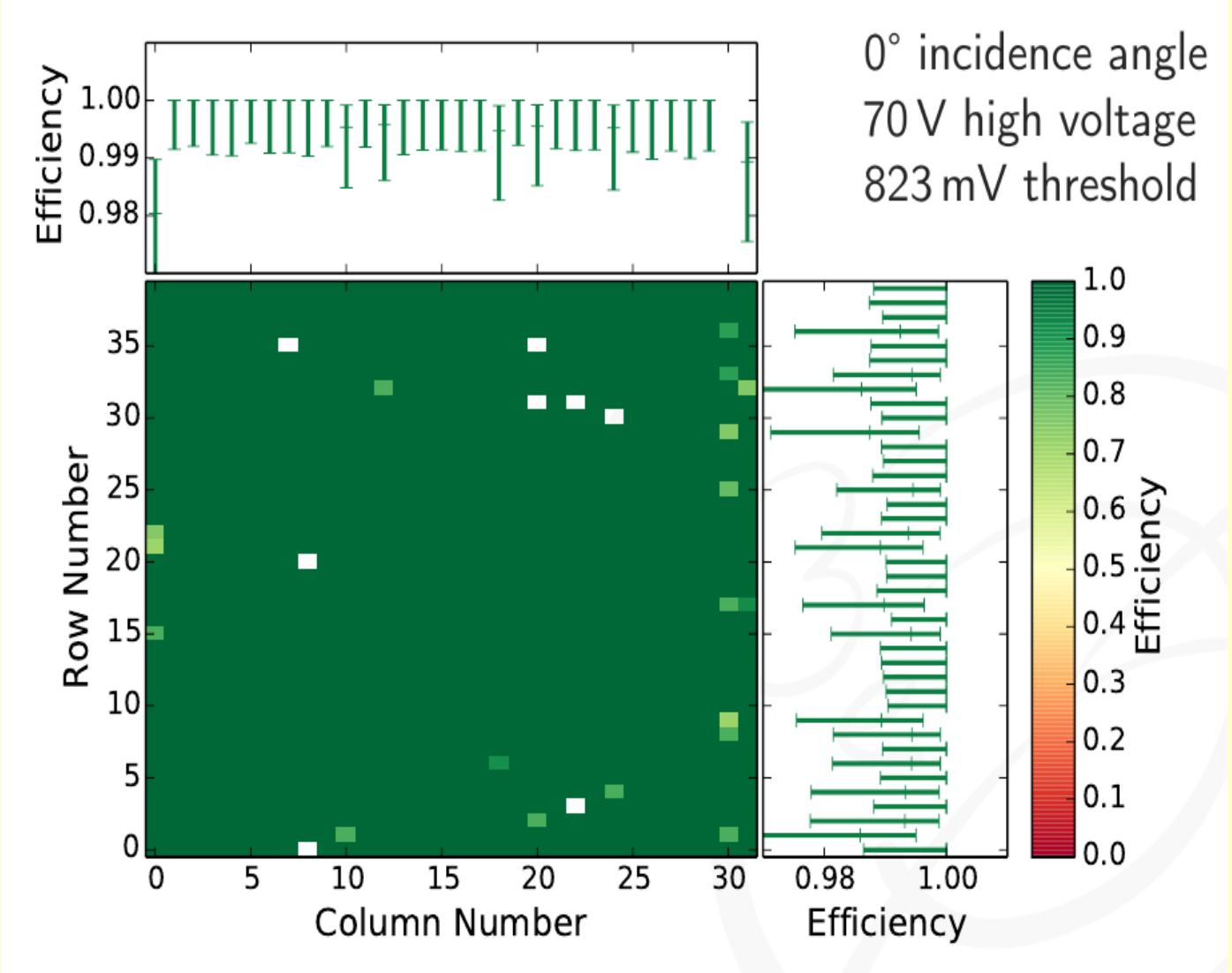
First Test Beam Result of Mupix4

DESY testbeam:

E_e = 3 GeV

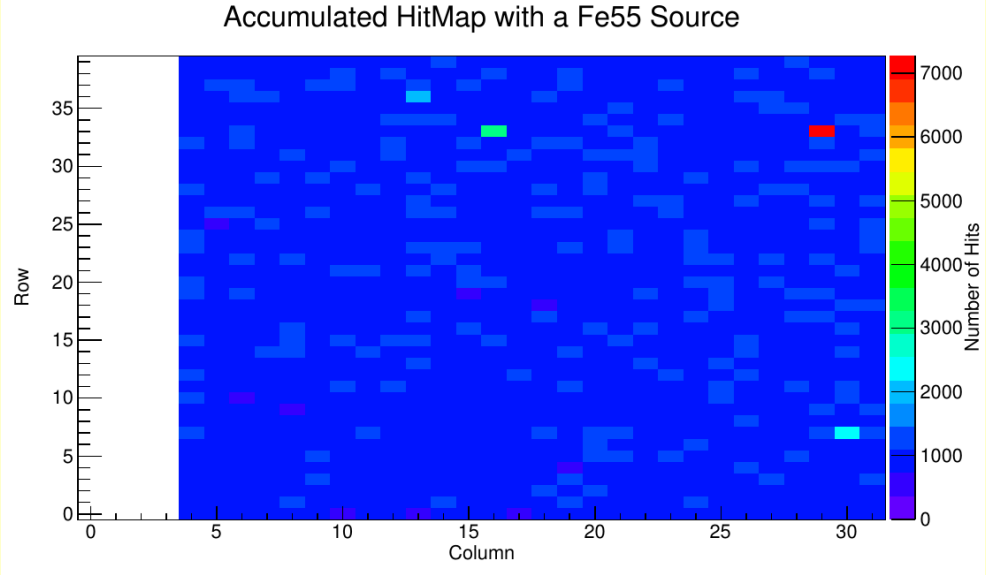
MuPix4 Prototype

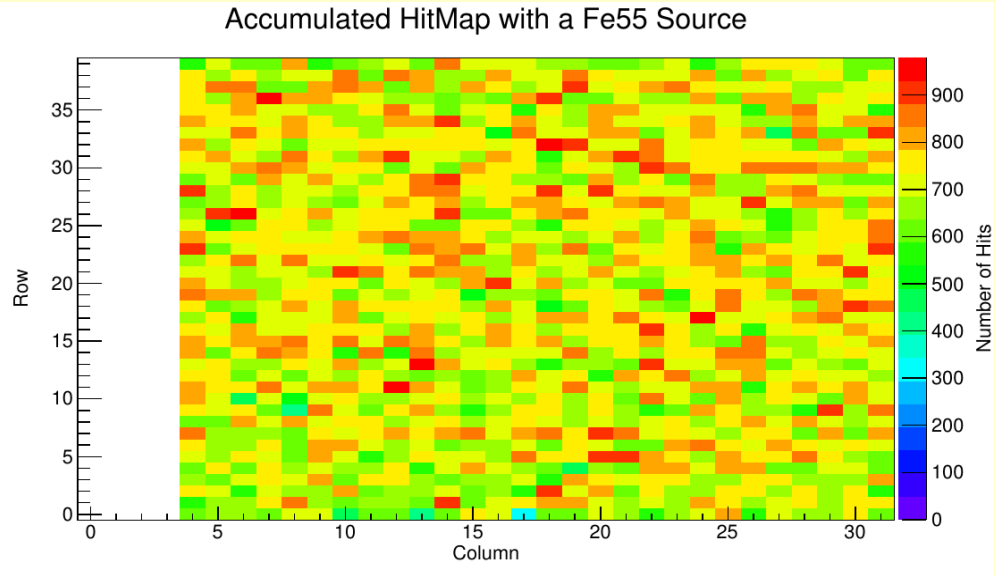




sensor efficiency > 99.5%

Threshold-DAQ Tuning Procedure

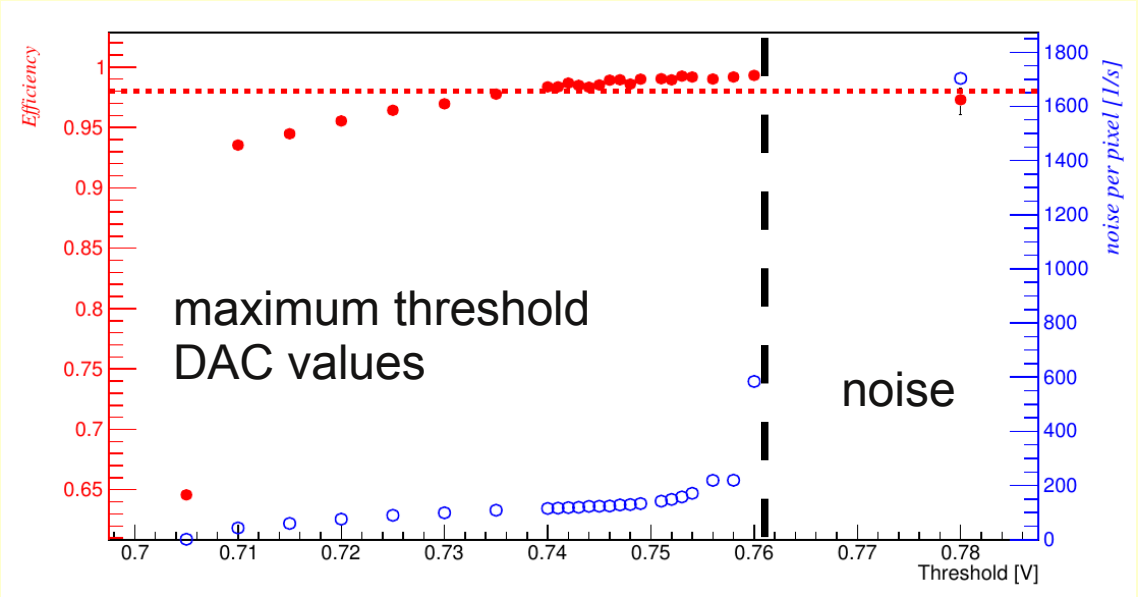




Untuned sensor
- all pixels working
- single noise pixel with 7kHz

Tuned sensor
- pixel rated between 300-900 Hz

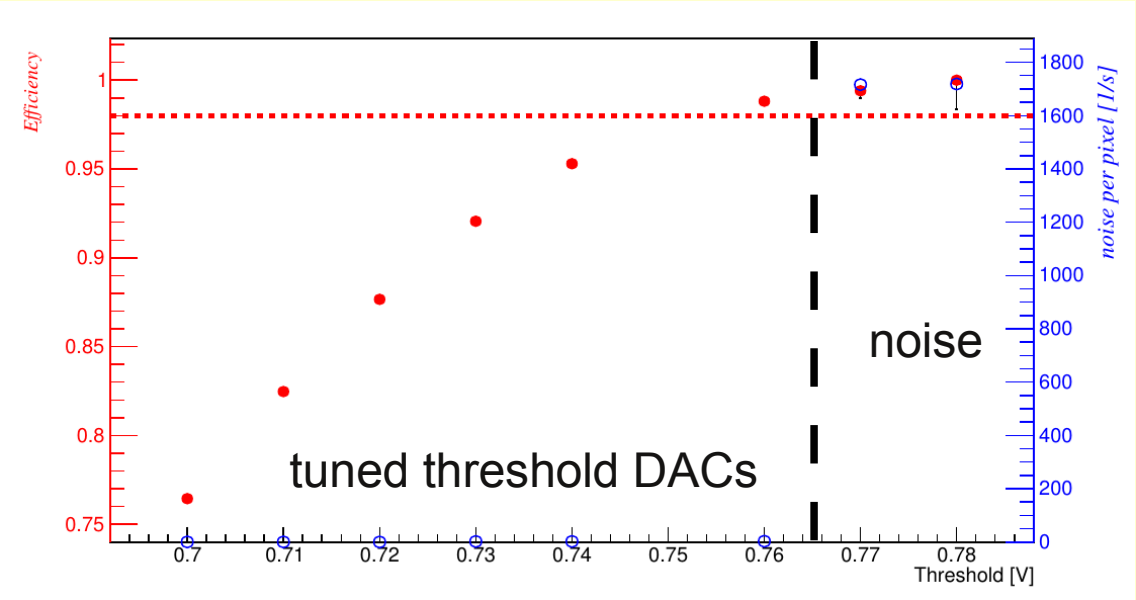
Test-Beam Results Mupix7 chip



operation mode:
"high power settings"

measured at **DESY** with
3 GeV electron beam

efficiency = 99% & noise=130 Hz
at V_{th}=0.75V



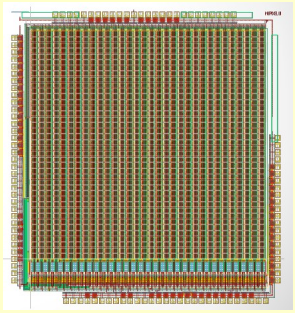
operation mode:
"high power settings"

measured at **MAMI** with
1 GeV electron beam

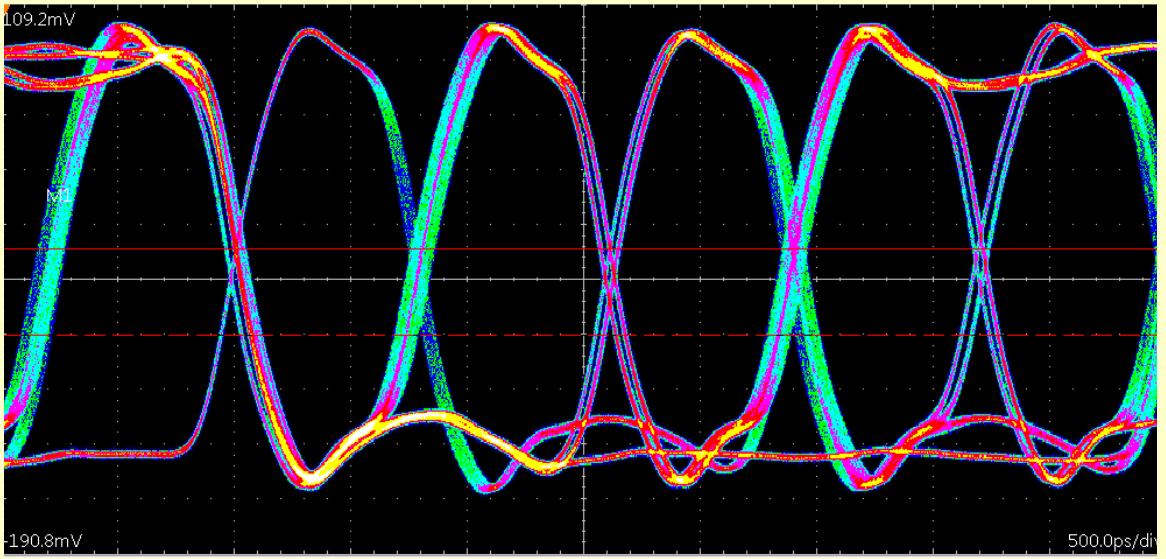
efficiency = 99% & noise= ~0 Hz
at V_{th}=0.76V

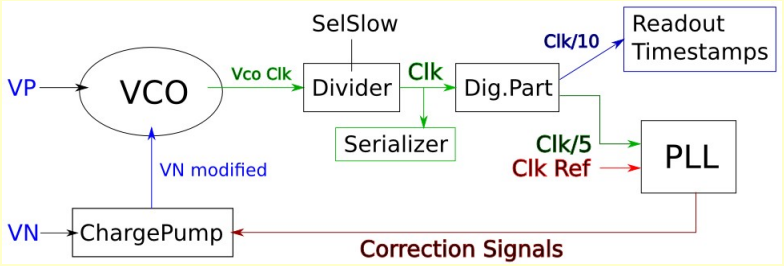
Commissioning of Mupix7 Gigabit Link

Mupix7 serial RO

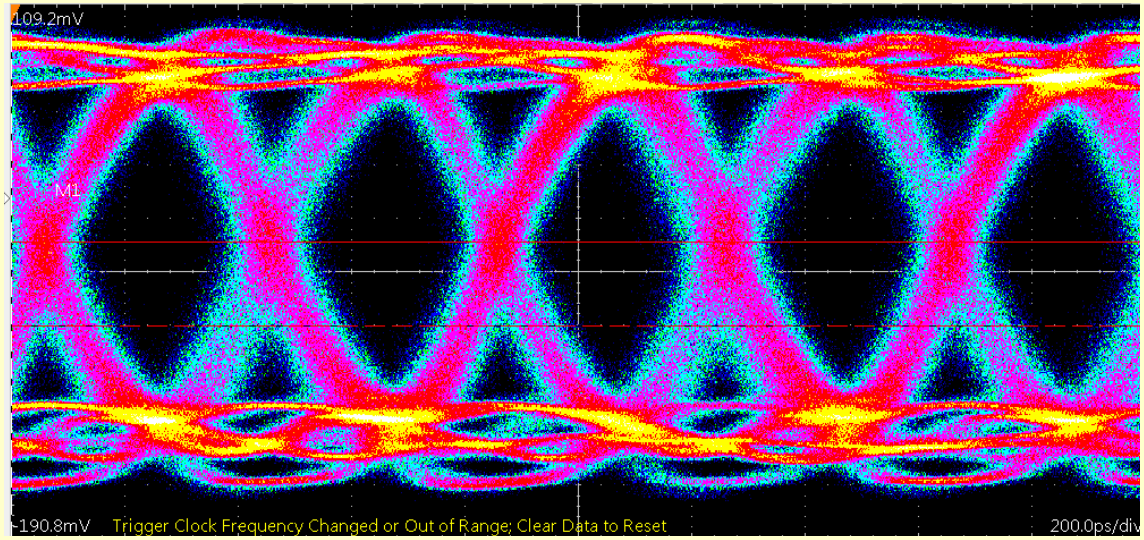


1.25 Gbit/s

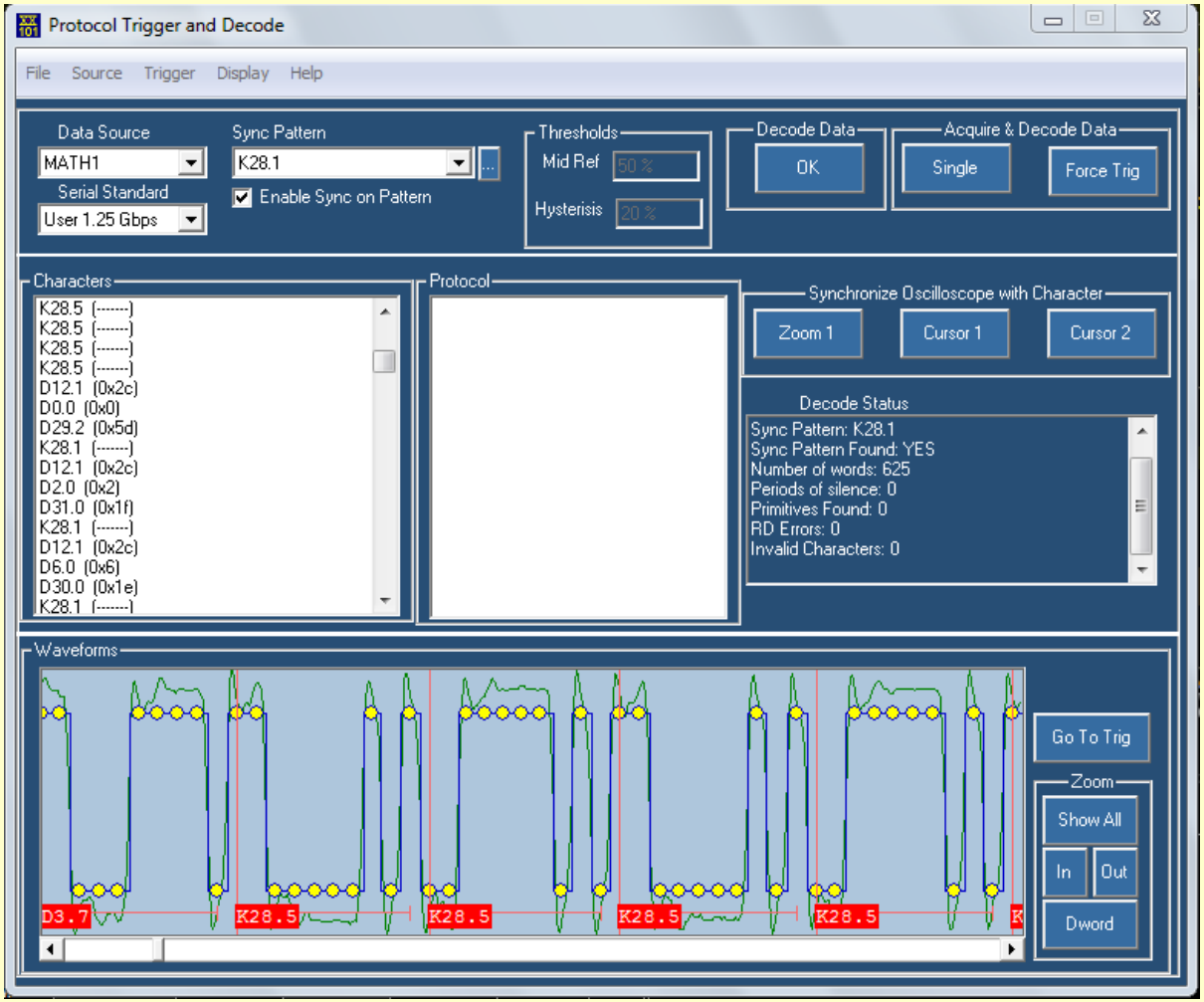


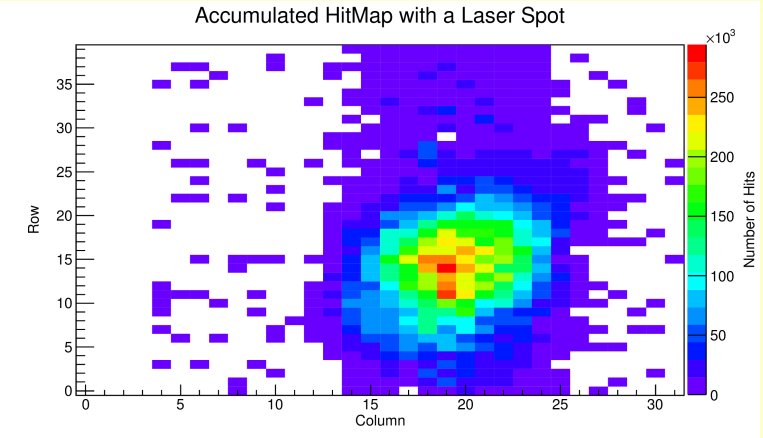


2.5 Gbit/s



First Mupix7 Data over Serial Link



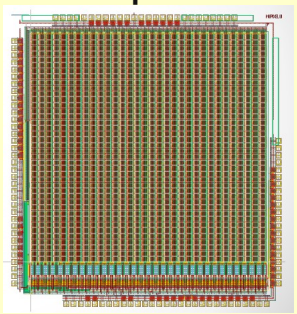


Laser Spot visible after decoding hit addresses

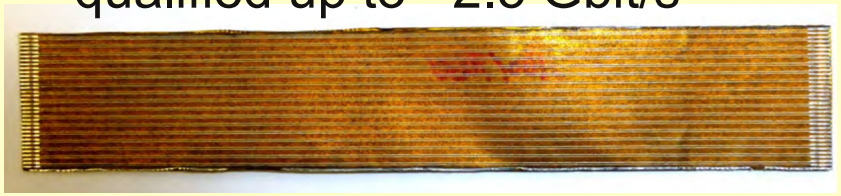
10/8 bit encoded data → measurement of bit error rates

Mupix7 over Flexprints Readout

Mupix7



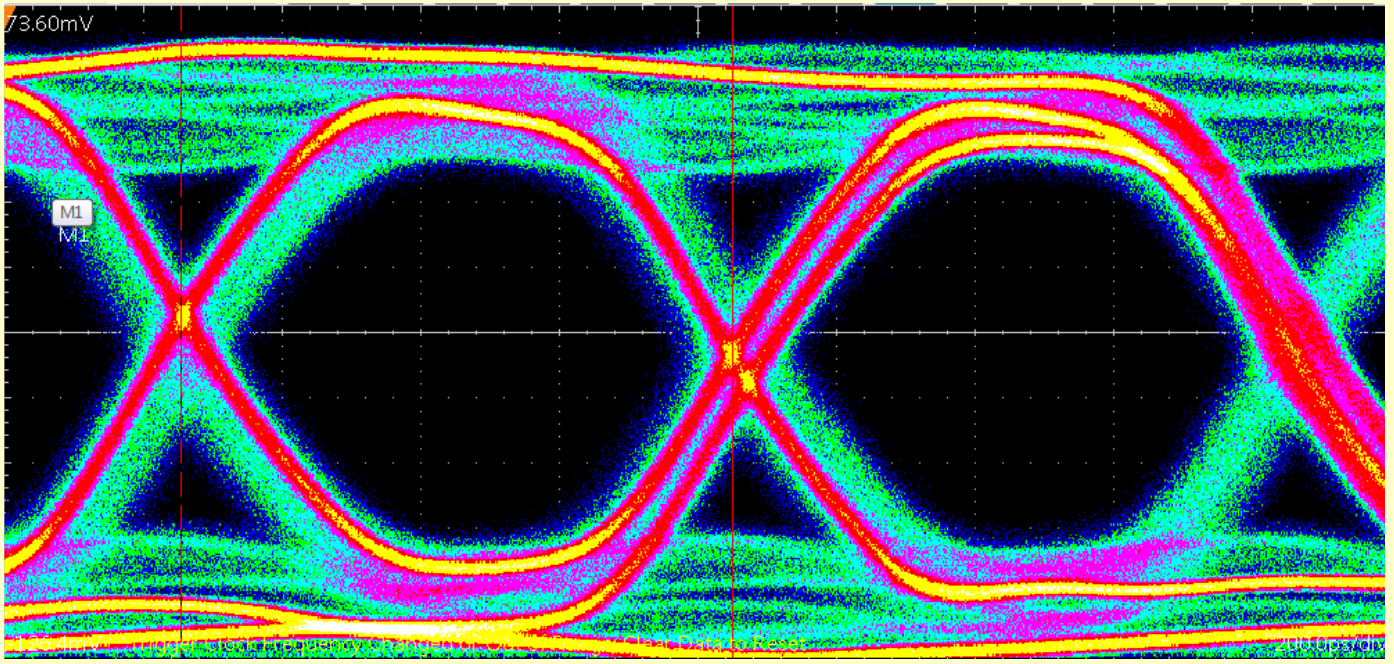
self-made (lasered) flex-prints
qualified up to ~2.5 Gbit/s



FPGA board

Stratix4

1.25 Gbit/s



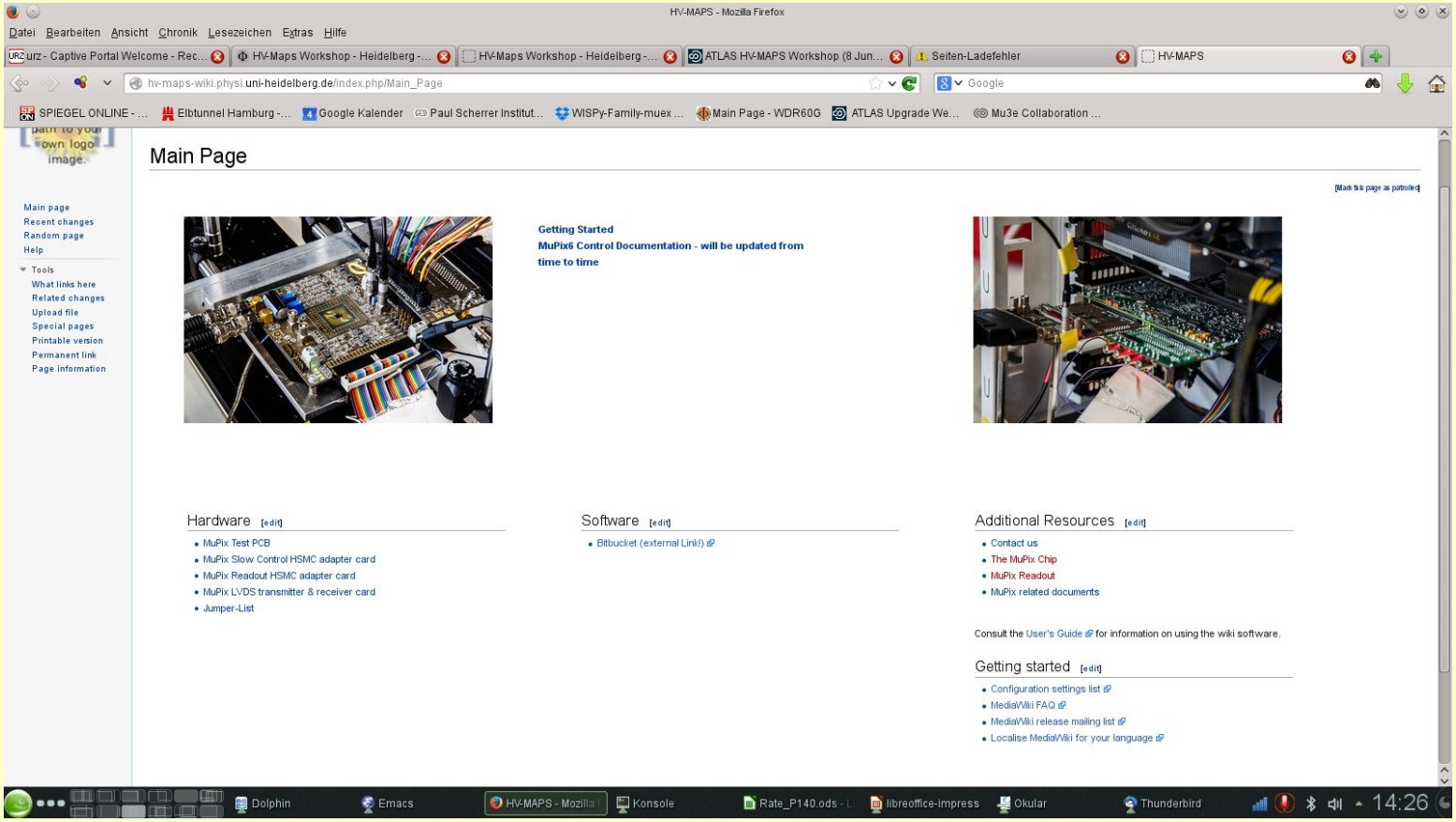
→ no transmission errors observed: BER< 10^{-14}

Mupix6 Test Boards Available

For those who want to test or irradiate Mupix6 chips:

~ 10 test boards and documentation available

→ we are happy to help people to get acquainted with the test setup



Conclusions

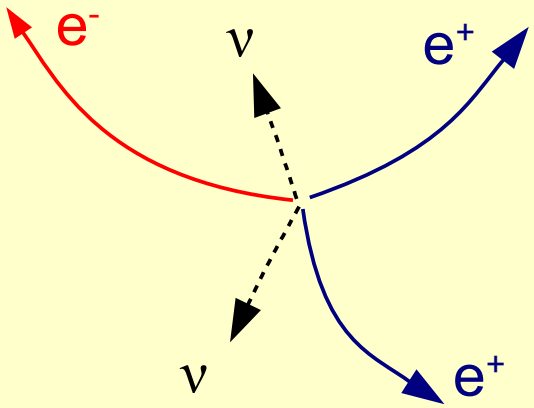
- Fully functional Mupix7 prototype is working!
- All requirements fulfilled except power consumption which is probably to high
- Further improvements planned:
  - higher resistive substrate → larger signal
  - improvements on comparator
  - ...
- Submission of large scale chip (2cm) in 2016 (new AMS H18 process).

THANKS to all contributing to this big success!

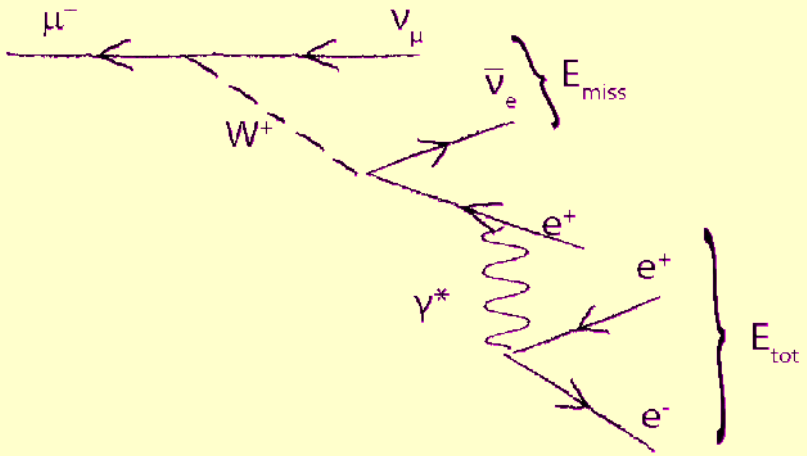
Backup

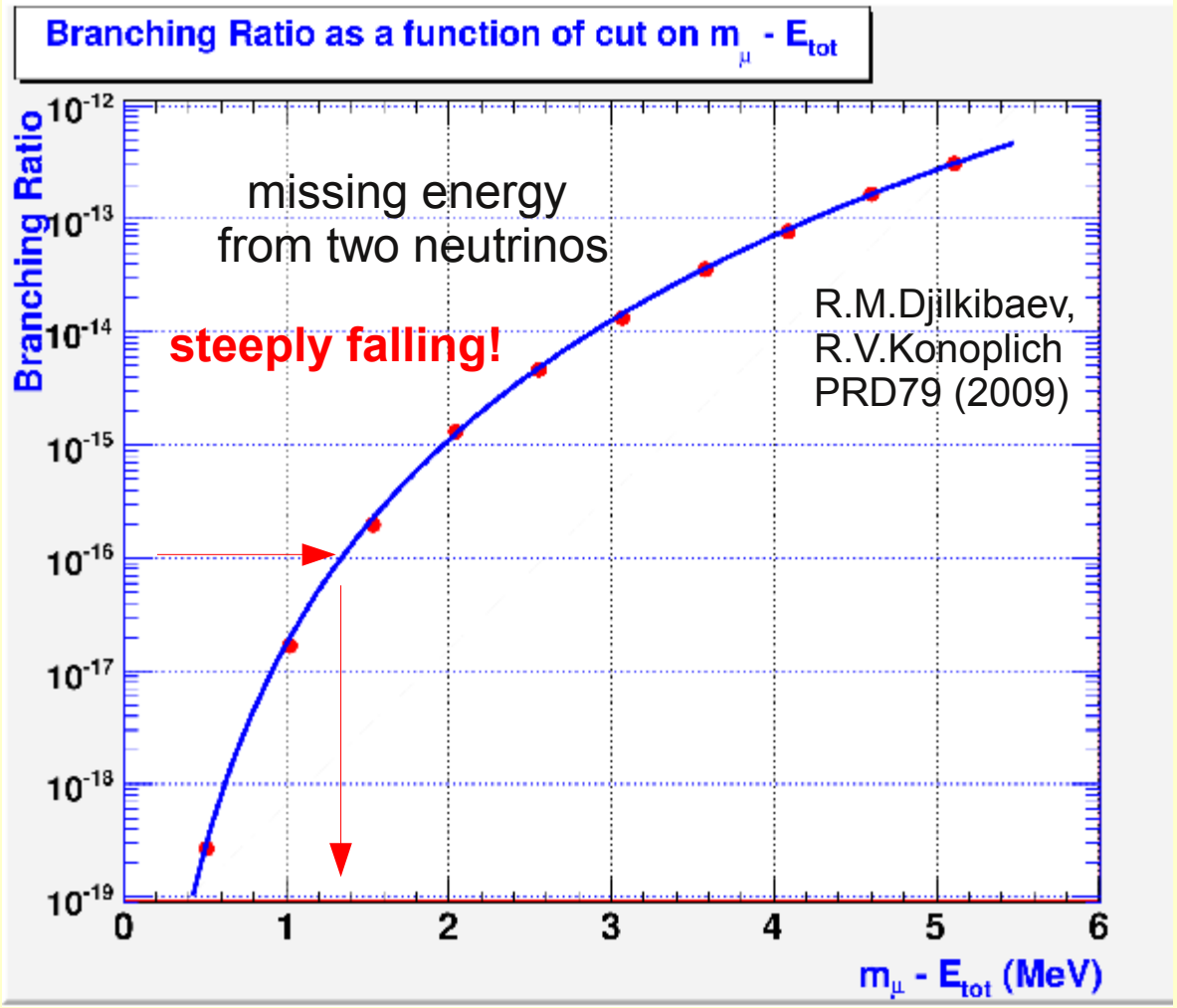
Backgrounds

Irreducible BG: radiative decay with internal conversion



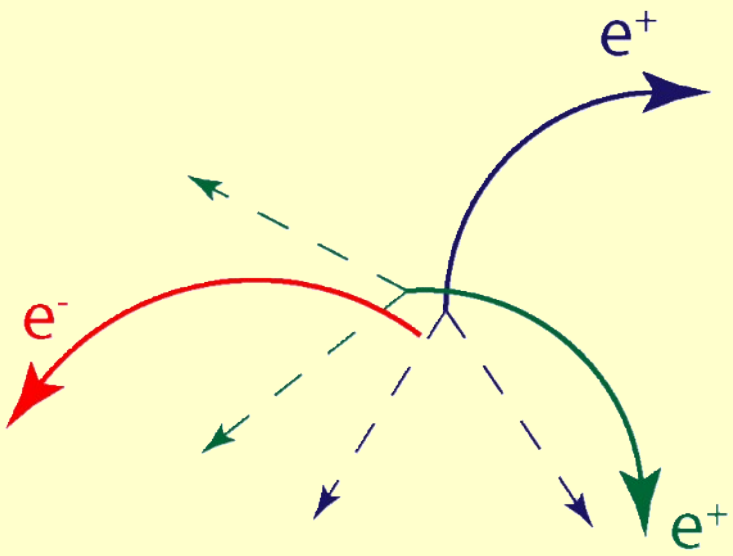
$Br(\mu^+ \rightarrow e^+e^+e^- \nu\nu) = 3.4 \cdot 10^{-5}$

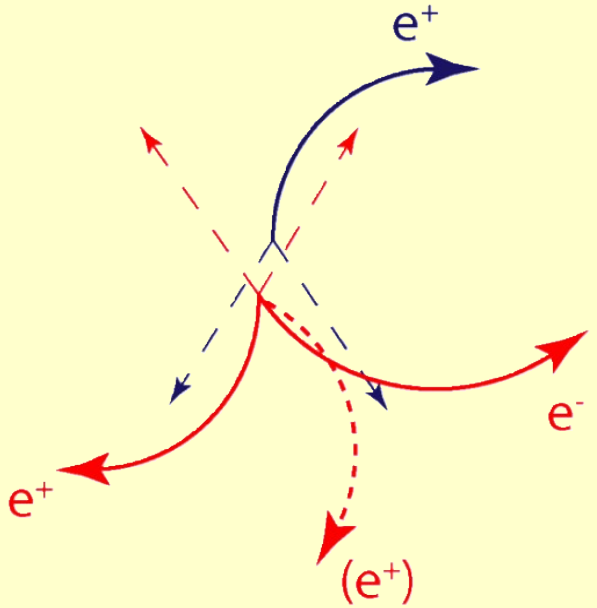




Accidental Backgrounds

- Overlays of two normal muon decays with a (fake) electron
- Electrons from: **Bhabha scattering**, photon conversion, mis-reconstruction





Need excellent:

- **vertex resolution** $\sigma_{vtx} \sim 200-300\,\mu m$
- **timing resolution** $\sigma_{time} \leq 0.1-1\,ns$
- **kinematic reconstruction** $\sigma_{M_{eee}} \leq 0.5\,MeV$